



Enabling Technologies for Next Generation Ultraviolet Astrophysics, Planetary, and Heliophysics Missions

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1 Executive Summary

Our study sought to create a new paradigm in UV instrument design, detector technology, and optics that will form the technological foundation for a new generation of ultraviolet missions. This study brought together scientists and technologists representing the broad community of astrophysicists, planetary and heliophysics physicists, and technologists working in the UV.

Next generation UV missions require major advances in UV instrument design, optics and detector technology. UV offers one of the few remaining areas of the electromagnetic spectrum where this is possible, by combining improvements in detector quantum efficiency (5-10x), optical coatings and higher-performance wide-field spectrometers (5-10x), and increasing multiplex advantage (100-1000x).

At the same time, budgets for future missions are tightly constrained. Attention has begun to turn to small and moderate class missions to provide new observational capabilities on timescales that maintain scientific vitality. Developments in UV technology offer a comparatively unique opportunity to conceive of small (Explorer) and moderate (Probe, Discovery, New Millennium) class missions that offer breakthrough science.

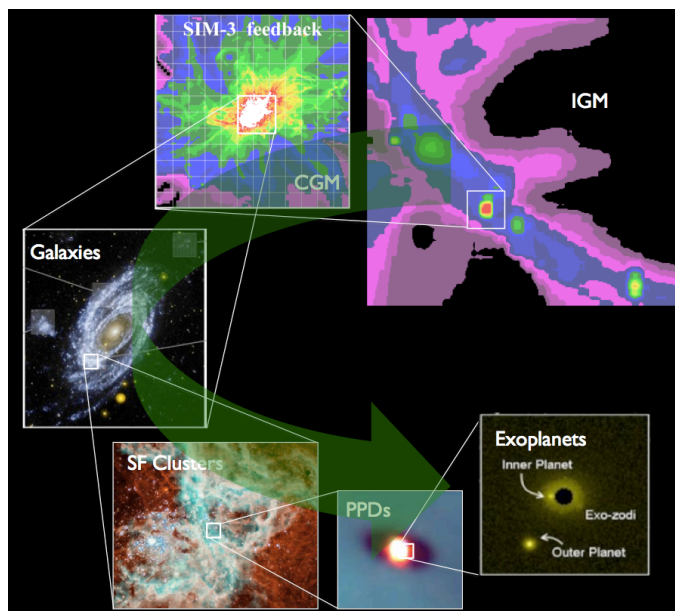


Figure 1. Explaining cosmogony. The next generation of missions will be design to explain the formation of structure and flow of baryons from the IGM to planets. UV measurements are critical for tracing the flow of gas (one of the principle root causes of structure formation) in the IGM, CGM, galaxies, and protoplanetary systems.

Our study began with the science, reviewing the breakthrough science questions that compel the development of new observational capabilities in the next 10-20 years. We invented a framework for highlighting the objectives of UV measurement capabilities: following the history of baryons from the intergalactic medium to stars and planets. In

astrophysics, next generation space UV missions will detect and map faint emission and tomographically map absorption from intergalactic medium baryons that delineate the structure of the Universe, map the circum-galactic medium that is the reservoir of galaxy-building gas, map the warm-hot ISM of our Galaxy, explore star-formation within the Local group and beyond, trace gas in proto-planetary disks and extended atmospheres of exoplanets, and record the transient UV universe. Solar system planetary atmospheric physics and chemistry, aurorae, surface composition and magnetospheric environments and interactions will be revealed using UV spectroscopy. UV spectroscopy may even detect life on an exoplanet.

Our study concluded that with UV technology developments within reach over the next 5-10 years, we can conceive moderate-class missions that will answer many of the compelling science questions driving the field.

We reviewed the science measurement requirements for these pioneering new areas and corresponding technology requirements. We reviewed and evaluated the emerging technologies, and developed a figure of merit based on potential science impact, state of readiness, required investment, and potential for highly leveraged progress in a 5-10 year horizon. From this we were able to develop a strategy for technology development. Some of this technology development will be subject to funding calls from federal agencies. A subset form a portfolio of highly promising technologies that are ideal for funding from a KISS Development Program.

One of our study's principal conclusions was that UV detector performance drives every aspect of the scientific capability of future missions, and that two highly flexible detector technologies were at the tipping point for major breakthroughs. These are Gen-2 borosilicate Atomic Layer Deposition (ALD) coated microchannel plate detectors with GaN photocathodes, and ALD-antireflection (AR) coated, delta-doped photon-counting CCD detectors. Both offer the potential for $QE > 50\%$ combined with large formats and pixel counts, low background, and sky-limited photon-counting performance over the 100-300 nm band. **Ramped AR coatings for spectroscopic detectors could achieve QE's as high as 80%!**

A second conclusion was that UV coatings are on the threshold of a major breakthrough. UV coatings permeate every aspect of telescope and instrument design. Efficient, robust, ultra-thin and highly uniform reflective coatings applied with Atomic Layer Deposition (ALD) offer the possibility of high-performance, wide-field, highly-multiplexed UV spectrometers and a broad-band reach covering the scientifically critical 100-120 nm range (home of 50% of all atomic and molecular resonance lines). **Our study concluded that UV coating advances made possible by ALD is the principle technology advance that will enable a joint UV-optical general astrophysics and exoEarth imaging flagship mission.**

A third conclusion was that the revolution in micro- and nano-fabrication technology offers a cornucopia of new possibilities for revolutionary UV technology developments in the near future. An immediate example is the application of new microlithography techniques to patterning UV diffraction gratings that are highly efficient and designed to enable wide-field, high-resolution spectroscopy. These techniques could support the development of new detectors that could discriminate optical and UV photons and potentially energy-resolving detection.

Relatively modest investments in technology development over the next 5-10 years could provide advances in detectors, coatings, diffractive elements, and filters that would result in an effective increase in science capability of 100-1000!

The study brought together a diverse community, led to many new ideas and collaborations, and brought cohesion and common purpose to UV practitioners. This will have a lasting and positive impact on the future of our field.

2 What happened at the Workshops?

Our first workshop was launched by a short course series that covered basics of the UV science drivers in “*UV Spectroscopy/Imaging and Science Questions*” (Paul Scowen, ASU), and key fundamental issues that had a broad impact on all UV instrument technologies in *What’s on the Surface* that discussed the importance of atomic level control of surfaces and interfaces both for electronic devices and optical elements (Drs. Michael Hoenk and Frank Greer). “*Nanotechnology and its relevance to UV Science*” (Prof. Nai-Chang Yeh of Caltech and Dr. Doug Bell of JPL) discussed new horizons and possibilities for sensing and optics modifications. The workshop was kicked off by technical talks were given by experts in cosmology, astrophysics, planetary sciences, protoplanetary science, and atmospheric studies of solar system planets and exo planets. Several talks also covered overview of various optics considerations, spectrometers, detectors, and challenges associated with each technology. A list of participants and the workshop agenda are on the KISS website and in appendices AI and A.II.

During the first workshop, as a result of our brainstorming and concept developments, we identified two to three major technology areas that could be enabling or have a major impact on a future UV mission. We also considered overlap with Optical goals. At the end of the first workshop we identified several breakout groups to further investigate our “wild ideas” as well as other ideas that had come up throughout the workshop. The interim study was used to flesh out some of the concepts. During the closing workshop in December the breakout groups were merged into three: 1) Detectors, 2) UV/Optical/Planetary/Exoplanet Science Drivers, and 3) Nanotechnology/Coatings/Filters. Further brainstorming, critical reviews of the concepts and existing or budding promising technologies narrowed the field. Results of these subgroup studies are summarized in the following sections. A list of the breakout groups and their members is included in Appendix IV. Some of the “wild ideas” are listed in the table below:

Table 1 — Blue-Sky Technology Ideas Discussed/Invented at KISS Workshop

Objective	Method	Assigned subgroup
Coronagraph	photonic crystals, ALD	Exo
Loss reduction & better coupling	black Si, black “X”, metamaterials, e-beam binary optics	Coatings
Lyman alpha notch	Multilayer	Coatings
Phase Correction	Metamaterials, ALD	Nano
Filtering	Metamaterials	Nano
Visible blocking	Al mesh, Wood’s filters (thin film)	Nano
Better photon coupling	Winston cone	Nano, Detectors
Polarization sensitivity (or lack thereof)	Metamaterials	Nano, Exo
Field-engineered backside-illumin. SPAD	MBE-graded delta-layer	Detectors
Better mirrors	high-T plasma ?	Coatings, Exo
Interferometry	cubesats?	
Narrow-band tailored response detector	quantum cascade detectors (QCD)?	Detectors
Visible distinction	nano detectors, ultrathin, 2-color with gain	Detectors
Rad-hardening of backside-illuminated Si	replace with Si ₃ N ₄	Detectors
Low-bandgap material for E resolution	MCTs substrate removed	Detectors
SPUD-2 / low-dark SPAD	vertical structure	Detectors

3 Science Opportunities Enabled by New UV Technologies

We stand at the threshold of constructing a complete picture of the origin and evolution of the Universe. The conditions that seeded the growth and evolution of large-scale structure, galaxies, and their constituents are known from studies of the cosmic microwave background. Major efforts are underway to understand the nature of the Dark Energy that dominates the mass-energy density of the Universe, and the nature of the Dark Matter that drives structure formation. HST and the Keck Observatory have delineated the history of galaxy formation and evolution, and future planned observatories such as JWST and TMT will search for the first star clusters and galaxies to complete this history.

The next step, the grand challenge of the next few decades, will be to explain this cosmic history. How does matter starting at astoundingly tenuous density collapse by 24 orders of magnitude in density to ultimately form stars and planets? How does the nebulous intergalactic medium collapse into a cosmic web of filaments, in which gas flows to form and fuel galaxies over cosmic time. How does gas flow in and out of the circumgalactic halos of galaxies, with inflows fueling star formation and outflows from galactic superwinds seeding the IGM with new chemical elements. How does gas flow within galaxies and collapse in star forming complexes and thus regulate the ongoing growth of galaxies? How do protostellar clouds collapse to form massive and low mass stars, and how do protostellar disks grow and ultimately form planetary systems?

These questions of cosmogony are multiwavelength and engage a large segment of the astrophysics enterprise. However, there are particularly compelling, broad, and definitive measurements that can be made with new space missions in the Optical/near-IR and especially the Ultraviolet. This is the result of a confluence of three streams. Discoveries from UV-capable astrophysics missions in the last decades, notably FUSE, HST, and GALEX, as well as from rest-UV observations of the high redshift universe in the optical, have demonstrated that UV observations have enormous diagnostic power to trace gas and star formation over an enormous range of scales and densities. Theorists now predict that UV emission will give a completely new and informative picture of the growth of structure in the Universe from the IGM to planets. To date, all UV measurements have been based on technologies developed in the 60's and 70's, and are thus profoundly limited in sensitivity and scope. UV technology has been limited by: low quantum efficiency, low reflectivity, high background, and modest fields of view and spectral multiplexing. UV technology is poised to make gigantic strides in quantum efficiency, background, reflectivity, field of view, and multiplex advantage. This final stream, when fused with the demonstrated discovery potential, means that modest investments in new UV technology will enable ground-breaking new UV missions that can begin to answer the age-old questions of cosmogony in the next 10-20 years, questions that cannot be answered by any other observation. The goal is to enable revolutionary, not incremental, new measurements, that unite the entire community and justify the high cost of new missions.

We note that UV measurements, because of their exquisite sensitivity to atomic, ionic, and molecular constituents over a wide range of temperatures, will continue to be a key component

of planetary and heliophysics missions of the future, and therefor will greatly benefit from the technology developments driven by the photon-starved astrophysics applications.

Table 2 — Cosmogy Questions from NWNH and Required UV/Optical Measurements

	O	OUV		UV		
	HCI/S	HRI	WFI	HRS	MOS	IFS
COSMOLOGY & FUNDAMENTAL PHYSICS						
<i>HOW DID THE UNIVERSE BEGIN?</i>						
<i>WHY IS THE UNIVERSE ACCELERATING?</i>			X		X	
<i>WHAT IS DARK MATTER?</i>		X	X			
<i>WHAT ARE THE PROPERTIES OF NEUTRINOS?</i>						
GALAXIES ACROSS COSMIC TIME						
<i>HOW DO COSMIC STRUCTURES FORM & EVOLVE?</i>		X	X	X	X	X
<i>HOW DO BARYONS CYCLE IN & OUT OF GALAXIES, AND WHAT DO THEY DO WHILE THEY ARE THERE?</i>		X	X	X	X	X
<i>HOW DO BLACK HOLES GROW, RADIATE, AND INFLUENCE THEIR SURROUNDINGS?</i>		X	X	X	X	X
<i>WHAT WERE THE FIRST OBJECTS TO LIGHT UP THE UNIVERSE AND WHEN DID THEY DO IT?</i>					X	X
GALACTIC NEIGHBORHOOD						
<i>WHAT ARE THE FLOWS OF MATTER & ENERGY IN THE CIRCUMGALACTIC MEDIUM?</i>		X	X	X	X	X
<i>WHAT CONTROLS THE MASS-ENERGY-CHEMICAL CYCLES WITHIN GALAXIES?</i>		X	X		X	X
<i>WHAT IS THE FOSSIL RECORD OF GALAXY ASSEMBLY FROM THE FIRST STARS TO THE PRESENT?</i>		X	X	X	X	
<i>WHAT ARE THE CONNECTIONS BETWEEN DARK & LUMINOUS MATTER?</i>					X	X
PLANETARY SYSTEMS & STAR FORMATION						
<i>HOW DO STARS FORM?</i>		X	X	X	X	X
<i>HOW DO CIRCUMSTELLAR DISKS EVOLVE & FORM PLANETARY SYSTEMS?</i>	X	X	X	X	X?	X
<i>HOW DIVERSE ARE PLANETARY SYSTEMS?</i>	X					
<i>DO HABITABLE WORLDS EXIST AROUND OTHER STARS, & CAN WE IDENTIFY THE TELLTALE SIGNS OF LIFE ON AN EXOPLANET?</i>	X					
STARS AND STELLAR EVOLUTION						
<i>HOW DO ROTATION & MAGNETIC FIELDS AFFECT STARS?</i>			X	X	X	
<i>WHAT ARE THE PROGENITORS OF TYPE Ia SUPERNOVAE</i>			X	X	X	
<i>HOW DO THE LIVES OF MASSIVE STARS END?</i>			X			X

One of the principal goals of this KISS study was to delineate the key science questions and measurements and show how these drive our needs for new technology. Our program of cosmogony can be broadly grouped into three areas:

1. Tracing the flow of baryons into galaxies, the formation of large-scale structure, galaxy assembly.
2. Following the cycles of star formation, chemical enrichment, and feedback (within galaxies and out of them)
3. Understanding the formation and evolution of stellar and planetary systems, including protoplanetary systems, detection and characterization of exoplanets, and the precision physical studies enabled by observations within our solar system.
4. In addition, a major advance in observational capability always results in profound new discoveries.

3.1 Mapping the flow of Baryons from the IGM to CGM to and from Galaxies

The odyssey of matter begins in the tenuous cosmic web, formed by the collapse of dark matter and baryons into a complex of walls, filaments, and denser structures formed at their intersection. This is the architecture of the Universe in which galaxies form and that fuels the growth of these galaxies with gas over cosmic time. Because of its exquisite sensitivity to tenuous gas and the abundant ions of Hydrogen, Carbon, Oxygen, and other important elements, UV spectroscopy is the only tool available to diagnose the temperature, ionization, and density of this gas. Past work has exploited high spectral resolution UV absorption spectroscopy using background QSOs to probe the IGM. New developments in UV technology are poised to offer a paradigm shift in these measurements. Because of the low number of background QSOs, absorption line measurements have provided only single line-of-sight probes of the IGM distribution. What we have lacked is the ability to map, except in a crude statistical fashion, the distribution of IGM. Mapping offers profound new physical insight and crucial tests of cosmogenic theories. With maps we can delineate the relationship and co-evolution of IGM, large-scale-structure, and galaxies. We can trace the flow of gas from the IGM to the circum-galactic medium (CGM) of galaxies, to the galaxies themselves, and discover gas flowing out of galaxies into the CGM and IGM with energy and newly formed elements. We can use the IGM to trace dark matter in the linear and near-linear growth regime. Finally, we can locate the majority of the baryons, most of which have not formed galaxies or stars, both in real space and in the phase space of density and temperature.

In recent decades, the evolution of universe's baryons has been revealed in remarkable detail. Early universe quantum fluctuations imprinted the otherwise highly uniform medium of dark matter, photons, baryons, and leptons with a scaffolding of dark matter overdensities. These dark matter overdensities provided the template large scale cosmological structure into which baryons gravitationally collapsed. The collapsing baryons interacted strongly with the photons such that the photon pressure increased monotonically with the baryon density. Eventually photon pressure would build up sufficiently enough to eject the baryons from the gravitational wells of the dark matter overdensities, creating regions of baryon underdensities. Moreover, the oscillating baryons would feedback to the ambient medium by launching isotropic density waves radially

outward that would later fuel the growth of galaxies and set the characteristic scale of galaxy separations in the present day universe. During the era of recombination the regions of overdensity (collapsing) and underdensity (expanding) are frozen in as the acoustic oscillations cease. Observations of the TT spectrum of the cosmic microwave background, its curlless polarization, the abundances of the elements and the baryon acoustic oscillations signal in present-day galaxy distributions provide firm observational evidence for the evolution of baryons prior to and during the era of recombination. The dynamics of baryons post-recombination era are then controlled by gravitational collapse and radiative cooling in regions of overdense dark matter halos and universal expansion in regions of underdensity. It is in this era and leading up to the present day where the observational data becomes more scarce.

In order for galaxies to form, condensations of baryonic matter more than 10^7 times more dense than the average must precipitate from the ambient medium. Understanding the details of galaxy formation from this IGM and their evolution within it, as well as the growth of larger scale structures, are major objectives of modern astrophysics. Unfortunately, key observational evidence is lacking to confirm or disconfirm dominant ideas on the topics. Ingredients present in all models of galaxy formation are the inflow of baryonic matter from the IGM into the galaxies and chemical and mechanical galactic feedback in the form of stellar winds, supernovae shocks and ejecta, and active galactic nuclei. While there has been ample evidence of the latter, the evidence for material flowing into galactic potentials is severely lacking. As a result, theorists and modelers are left to use simplified semi-analytical models and assumptions to make progress. What is needed is a mapping of the IGM and CGM in both spatial, kinematic, and metallicity/age space.

Much of what we currently know about the IGM/CGM has been discerned from QSO absorption line spectroscopy studies. QSOs, while numerous, are sufficiently rare that we have only been able to map pencil-beam cross-sections through the IGM/CGM. The complex and overlapping morphologies of accreted substructures seen in galaxy accretion and growth of large scale structure simulations require full-sky surveys to trace and disentangle the observed halo streams and map the IGM/CGM filaments. Observations in the UV are preferable as the dust extinction law is maximum in UV and there are many strong atomic and molecular transitions of H, D, H₂, He, C, O, Mg, Si, S, and Fe. Moreover, state of the art absorption line detections are more sensitive than 21cm emission measurements. Among the various absorption line systems seen in QSO spectra: the Lyman alpha forest, Lyman Limit Systems (LLS), Damped Lyman alpha (DLA) systems, Helium equivalent systems, and metal absorption line systems, each serves as a unique probe of intervening material. The key to improved mapping is to vastly increase the number of UV background sources. This is achievable via a substantial upgrade in sensitivity above recent satellites like GALEX to acquire many more QSO absorption spectra with excellent statistics and to allow the emergence of face-on external galaxies as useful UV sources for these studies. According to estimates, the LSST should deliver QSO sky densities $> 1000 \text{ deg}^{-2}$ after a 10-year survey. A dedicated UV, multi-object spectroscopy survey should be able to deliver at least hundreds of UV spectra per square degree within a reasonable time frame.

An additional scientific outcome from mapping the IGM/CGM more comprehensively than has ever done before is that we will also be able to address the “missing baryons” problem and probe the Warm-Hot IGM (WHIM). Indications of the total baryon fraction of the universe are available from primordial nucleosynthesis of the elements at $z \sim 10^9$, from the heights of the CMB TT spectrum’s acoustic peaks at $z \sim 1100$, and from Lyman alpha forest measurements of the baryon density at $z \sim 3$. All three measures converge on a universal baryon density of ~ 0.04 . Current measurements of detected baryons only account for $\sim 20\%$ of the required baryons, however. The WHIM is expected to contain an additional fraction of 25% to 40% of the universal baryon density.

There are two approaches to mapping. Absorption line observations remain the most sensitive to the smallest densities and trace constituents. By combining gains in sensitivity with field of view and multiplexing, a *tomographic threshold* can be reached. At this point the number density of background sources rises to the point at which multiple lines of sight intersect single cosmic structures, and true 3D maps can be constructed of the intervening gas. This point could be reached by using galaxies and faint AGN as background sources. While high resolution UV spectroscopy is always aided by the largest apertures, major advances could be made by increasing detector quantum efficiencies from typical 5-10% to $>50\%$. The ultra-dark UV sky combined with targeting faint objects at high spectral resolution immediately drives us to detectors with the lowest possible dark background.

Finally, coating reflectivity drives the performance of high-resolution spectrographs. Reflectivity improvements offer the possibility of high-performance spectrographs that could obtain multiplexed spectra of 10-100 objects simultaneously, effectively increasing the mission efficiency by the same 1-2 orders of magnitude. Of equal importance, extending coating performance to the 100-120 nm range is critical, because key atomic lines from Hydrogen, Carbon, and Oxygen appear here. While these can be measured at longer wavelengths when redshifted, studies of nearby systems offer the opportunity to make detailed physical models of the flow of gas, energy, and chemical elements.

The second approach to mapping is completely new. With new developments in UV technology it will be possible to detect the very faint *emission* from the IGM. Mapping emission offers fundamentally new information that will complement QSO absorption line measurements:

- Detection of low filling factor or warm-hot gas missed by absorption lines (e.g., COS),
- 3D maps of gas and metals; spatial relationship of IGM, CGM, galaxies, and QSOs;
- IGM cloud sizes, structure, density, mass;
- Kinematic mapping and gradients that probe flows, rotation, mechanical, radiation inputs;
- Probe of cooling, energetics, ionization, recombination, and multi-phase structure;
- Statistical connection between CGM and galaxy properties.

UV emission spectroscopy will be enabled by new developments in technology. High QE, ultra-low-noise photon-counting detectors are essential. Wide field, wide band-pass integral field and multi-object spectrometers require high performance optics with highly reflective coatings.

Coatings that extended to the deep UV (100-120 nm) offer the opportunity to map local OVI1033Å and HI Lyman lines. With relatively modest investments in new technologies new missions can be formulated that will make the first true images of the cosmic web.

Because of the steepness of the QSO luminosity function in the UV, an order of magnitude improvement in instrument sensitivities over current capabilities vastly increases the number of available background targets and improves the spatial sampling to scales of several arcminutes. Such investigations require spectroscopy with spectral resolutions of $R \sim 30,000$ -100,000. Broad wavelength coverage, 100-300 nm, ensures wide redshift sampling of the IGM and selection of a wide range of elements and ionization states. A multi-object capability using microshutter arrays would improve observing efficiency and give the potential to undertake tomography of the IGM and galaxies. Increases in telescope aperture and improvements in detector QEs and optics throughputs (via improved coatings with excellent broadband reflectivity) are all important. The UV detectors should have high pixel counts to support the broad wavelength coverage required.

Direct imaging of diffuse gas frees IGM studies from the need for background targets and allows for full mapping of the structure of the IGM and how it interacts with galaxies. These investigations require wide field imaging at low to moderate spectral resolution ($R \sim 3000$) with an IFU or MOS capability. Moderate spatial resolution (~ 1 arcmin) is also required. The technology requirements include very low detector backgrounds and low instrument scattered light so that observations of the faint, diffuse emission are sky-limited. To enable observations of both the diffuse emission and the galaxies, moderate detector dynamic range is necessary. Photon-counting detectors are desirable to further reduce noise.

3.2 Following the cycles of star formation, chemical enrichment, feedback in and out of galaxies

In our quest for a new understanding of the forces that drive galaxy evolution and the conversion of baryons into stars, we turn to the galaxies themselves, and in particular to the forces driving star formation. These can be studied in a powerful new way with new UV and advanced OIR capabilities. HST has proven the importance of OIR imaging for mapping the growth of galaxies over cosmic time. GALEX has shown the power of UV imaging to delineate star formation across an enormous range of physical regimes, from the lowest to the highest mass, from extremely low levels of star formation tracing the final trickle of gas from the IGM to the massive starbursts that dominated galaxy growth in the “epoch of star formation”. High resolution, wide-field UV imaging will probe star formation in all its variations and modalities on scales small enough to delineate the physical triggers, and in samples numerous enough to separate the influence of environment, local gas density, local stellar and gas velocity dispersion, gravitational instabilities, and local gas flows in determining the local and global star formation history in galaxies. Resolved UV stellar photometry could be exploited in future missions to deconstruct the recent star formation history and initial mass function in diverse physical regimes of a representative set of nearby galaxies. Wide field UVO imaging could answer the following questions: Does the formation of massive stars in a particular locale affect and dictate the subsequent star formation across that region. What is the fundamental difference between

starburst star formation and the more common disk modes we see in disk star forming regions in our own Galaxy. What is the correct density and velocity structure associated with the stellar winds from massive stars, and how that inhomogeneity and clumping in their winds affect the transfer of energy and material to the ISM and the process of recycling of material from the stellar to the gas phase for the next generation of stars. What global processes govern the assembly and evolution of giant molecular clouds - since dominate the modes of star formation in galaxies, and the underlying process of stellar assembly.

UV spectroscopy of galaxies has lagged other techniques because of the limitations of UV technology. This is unfortunate since UV spectra harbor a cornucopia of physical diagnostics. UV spectra probe the age, and metallicity, and stellar mass distribution in newly formed stars, the distribution, dynamics, and chemical abundances of the Interstellar Medium from which these stars form, and the local and global impacts of stellar feedback in regulating star formation and driving gas flows in and out of galaxies. UV spectroscopy measures the all-important Lyman alpha line of Hydrogen. Mapping the spatial and kinematic distribution of this line in lower redshift galaxies may be the only way to interpret this strong line in the most distant, youngest galaxies observed by Keck, JWST, and TMT. Galaxies may have been responsible for reionizing the Universe at redshift $z \sim 8$. This can only be the case if ionizing radiation from young, massive stars can escape the ISM of the galaxies. Understanding this escape may only be possible in nearby galaxies that can be spectroscopically mapped in Lyman continuum (escaped ionizing) radiation.

Wide field UV imaging requires large-format, low-noise detectors with high QE and good red rejection from the detector or efficient UV filters. High-resolution imaging is far more sensitive with photon-counting detectors because of the very low UV sky background. Wide-field, imaging and highly-multiplexed UV spectroscopy requires the highest QE, low background, photon-counting detectors that can be assembled in large formats with high pixel counts in order to span broad wavebands simultaneously with large fields of view and spectrum count. These high-performance wide-field spectrographs in turn require highly efficient UV coatings that support multi-optic, highly corrected designs.

3.3 Understanding the formation and evolution of stellar and protoplanetary and planetary systems; detection and characterization of exoplanets, and precision physical studies enabled by observations within our solar system.

Finally, we seek to understand *how* matter collapses from giant molecular star-forming clouds to form protostars, protostellar and protoplanetary disks, stars and ultimately planets. While some of these phases are shrouded in UV/optical absorbing dust and can only be studied in the Far IR and radio bands, key evolutionary stages become visible in the UVO as the enshrouding dust is disrupted by feedback from the protostars. As protostars collapse residual angular momentum forces much of the material into a surrounding disk. This disk continues to feed the growing star, while magnetic activity in the protostar unleashes copious winds and jets that may regulate further gas collapse and stellar mass growth. Disk structure and evolution is the key to planet formation. The protoplanetary disk consists of gas, dust, and larger particles. Instabilities lead to

the formation of planetesimals that seed the growth of rocky, gas-giant, and ice-giant planets. While a basic picture exists no theory of planet formation has predicted the stunning diversity of observed exoplanets.

GALEX has shown that UV imaging allows us to quickly identify chromospherically active stars which are young and likely to harbor planets in the early stages of evolution, perhaps still radiating gravitational collapse energy. High resolution and high contrast UVO imaging and spatially resolved spectroscopy allows us to image and spectrally map protostellar jets, in order to understand the regulation of stellar mass by feedback. High resolution and high contrast UVO imaging and spatially resolved spectroscopy of protostellar/protoplanetary disks (PPDs) will allow us to directly search for structures indicating planet growth.

The lifetime, spatial distribution, and composition of gas and dust in the inner ~ 10 AU of young (age ≤ 10 Myr) circumstellar disks are important components to our understanding of the formation and evolution of extrasolar planetary systems. Molecular and atomic lines in the FUV (H_2 , CO, CIV, etc; 100 – 170 nm) are unique tracers of the disk gas and accretion timescales. For mature exoplanetary systems, transit spectroscopy enables a direct measurement of atmospheric composition and mass loss from extrasolar giant planets. The FUV band (115 – 170 nm) provides access to resonance line diagnostics of the primary atmospheric species (hydrogen, carbon, oxygen, etc) that are not readily observable at other wavelengths.

A premier goal of the next large optical observatory is direct imaging and spectroscopic characterization of nearby earth-like planets. This will require a large (4+ meter) aperture and some combination of ultra-high-contrast internal coronagraphy and/or an external occulter. The UVOIR and Exoplanet communities recognize that a large UVO mission almost certainly can only take place as a combined general-purpose UVO observatory and a Terrestrial Planet Imaging and Characterization mission.

Ultraviolet spectra are critical to our understanding of Earth-like worlds, particularly in light of the growing number of Earth-like planets detected orbiting low-mass stars (Borucki et al. 2011). A major source of uncertainty regarding the habitability of these worlds is the strength and variability of the local radiation field where liquid water can persist (the “habitable zone”). Ultraviolet radiation is important to the photo-dissociation and photochemistry of H_2O and CO_2 . It also enables the synthesis of biomarkers, including CH_4 and O_3 . Stellar flares may imbue the exoplanetary atmosphere with heavy doses of ultraviolet radiation, potentially catalyzing or retarding the development of biology on these worlds.

Our solar system, and the bodies and processes within it, form the critical link between our understanding of Earth and its evolution and exoplanets, stellar formation and the IGM. By studying the planets in our own solar system, we can better interpret our observations of exoplanets, with implications for understanding of stellar and planet formation. Ultraviolet spectroscopy is a critical method for probing solar system targets. Hubble Space Telescope discoveries have been crucial in furthering our knowledge of dynamic processes in a number of scientific areas within the solar system, and have been key in driving follow-on planetary

missions. The importance of a space-based UV facility for planetary studies was called out in the Planetary Decadal Survey (Visions and Voyages for Planetary Science in the Decade 2013-2022). Key planetary scientific areas include auroral studies at bodies such as Jupiter and Saturn, Io, Europa and Ganymede; atmospheric studies at Venus, Titan, the gas giants (Jupiter, Saturn) and ice giants (Neptune, Uranus) as well as thinner atmospheres (Mercury, Mars, Ganymede, Io, Pluto); cryovolcanism studies and searches (Europa, Enceladus, primitive bodies and other moons); neutral and plasma torus investigations; and studies of comets. For example, the dynamics of auroral and airglow spectral (100-350 nm) and brightness distributions reveals magnetospheric interactions with the solar wind and with planetary satellites. Ultraviolet stellar occultations discovered the spatially-confined cryovolcanic plumes in the south polar region of Enceladus and can be further utilized to search for and study activity at other small bodies. Furthermore, the density, thermal and compositional profiles of planetary atmospheres (including tenuous atmospheres) are probed with high vertical resolution using UV stellar occultations. Investigations of the surface compositions of the wide range of small primitive bodies throughout the solar system (NEOs to main-belt asteroids, Trojan asteroids, and KBOs) can be studied using the previously unexploited UV-visible region, as many of these bodies are still not understood and are often not spectrally active except in the UV-visible; thus understanding this spectral region and the implications for surface composition including organics and volatiles species, is important for understanding the history of our solar system.

The above science goals require high QE ($\geq 50\%$) photon-counting UV detectors with low background rates ($\leq 10^{-6}$ counts s^{-1} resel $^{-1}$), large formats to support wide-field imaging (at least $20' \times 20'$, with 40 mas resolution) and multiobject spectroscopy, and high performance ($\geq 90\%$) UV coatings to enable multiobject and imaging, moderate to high-resolution ($R > 3 \times 10^4$) spectrometers that can efficiently multiplex numerous star forming systems in nearby young associations and map some spatially. Perhaps most significantly, dovetailing the objectives of UV imaging and spectroscopy with Terrestrial Planet Imaging requires very high performance UV coatings on at least one and perhaps three telescope mirrors. Internal coronagraphs are likely to demand high uniformity and low induced polarization on the telescope optics. This requires new, ultrathin protective layers on Aluminum in order to cover simultaneously the Far (and perhaps even Deep) UV and optical bands while allowing for high contrast (10^{-10} system net capability) internal coronagraphy. Host star characterization and extrasolar giant planet transit spectroscopy will require high-sensitivity ($F_{\lambda} \sim 10^{-18}$ erg cm^{-2} s^{-1} \AA^{-1}) stable FUV spectroscopy, and photon-counting at moderate cadence ($\Delta t \sim 1$ sec) for planet transits, but much higher rates for solar system targets ($\Delta t \sim 1$ msec).

3.4 Opening discovery space

Remarkable new discoveries by GALEX and HST/COS have reminded us that large increases in observational capability lead to new discoveries. The UV technologies we have identified will make large increases in sensitivity and field of view, and enable highly multiplexed spectroscopy. This will support large surveys that are ripe for discovery of new and unexpected phenomena. One of these that has already shown great promise is time-domain astrophysics.

A variability survey in the UV would facilitate substantial advancement in several areas of astrophysical research including studying planets, stars, and galaxies. Below, we outline three such studies and their requirements.

Variability is one of the hallmark properties of active galactic nuclei (AGN), and in fact it was originally because of their extreme, often short timescale variability that the AGN phenomena was first associated with black holes, because of the extreme compactness of the emission regions. A UV variability survey would probe several of the regions necessary for understanding AGN.

Multi-object, time-resolved UV spectroscopy over wide fields will allow efficient characterization of stellar UV variability. This will address systematic uncertainties associated with characterizing exoplanet atmospheres via UV transit observations. This will also allow characterization of the magnetic activity level of stellar hosts. Finally, a stellar UV variability survey will enable a wealth of ancillary stellar science including characterization of cataclysmic variables and dwarf flare stars, for example.

Two exciting areas of transient research follow GALEX discoveries. Tidal capture flares result when massive but invisible black holes (“Inactive Galactic Nuclei”) tidally disrupts a star and accretes its gas, forming a several month long event that peaks in the UV. The properties of the event determine the black hole and stellar mass, and the rates provide a measurement of the demographics of otherwise silent massive black holes. Supernova explosions begin with a “shock-breakout” event as the core-collapse implosion creates a reverse, outwardly propagating shock wave through the stellar envelope dramatically heats the photosphere to UV-emitting temperatures. An initial very bright but very short (minute) time-scale “spike” has never been observed but may provide the strongest constraints on the supernova and its progenitor star.

Wide-field, high angular resolution, time-resolved UV imaging and spectroscopy on multiple timescales will allow the discovery of new UV variable and transient phenomena. There are multiple science drivers for such a survey including the discovery of new phenomena associated with AGN, supernovae, gamma-ray bursts, accretion disks, flare stars, stellar atmospheres, compact objects, and more.

4 Discovery-Enabling New Detector Technologies

4.1 Introduction

The ultraviolet region of the spectrum is an area of space study where major discoveries could be made possible in the near future with significant yet feasible gains from technology. Combined improvements in detector quantum efficiency (5-10x), optical coatings and higher-performance wide-field spectrometers (5-10x), will lead to a multiplied advantage (10-100x) over existing technology. Single photon counting is crucial as is a large number of pixels. The frontier measurements described in the previous section can only be performed with a new generation of UV detectors (Table 3).

Figure 2 shows an example of the improvement in data quality that would be expected from a high QE photon counting UV detector array with a large number of pixels, making a dramatic impact on discovery potential.

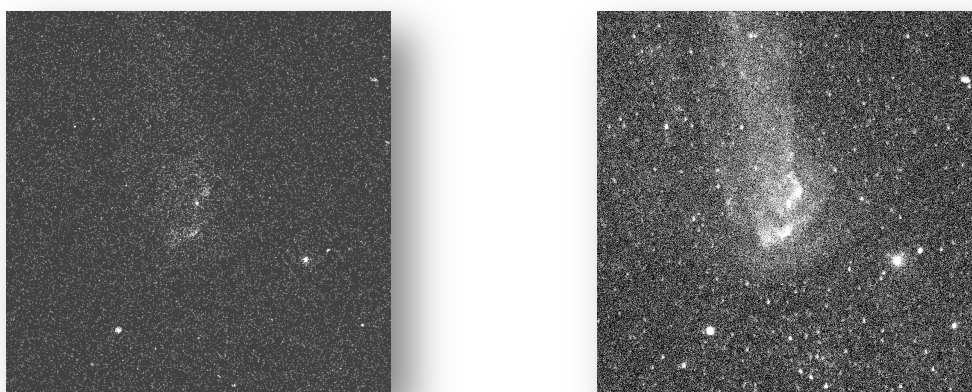


Figure 2 Illustration of the effect of detector quantum efficiency and low noise on discovery potential. The image on the left is a 100 s GALEX image of low surface brightness emission from the cloud of gas surrounding the star Mira. The image on the right is a 1600 s integration of the same field, yielding a S/N improvement of 4x. This degree of improvement is expected with UV enhanced L3CCDs compared to existing technology. Along with the low voltage operation and the general reliability of CCD detectors these improvements will enable a great leap in discovery.

As discussed earlier, during the first workshop, as a result of our brainstorming and concept developments, we identified several detector areas that could be enabling or have a major impact on a future UV mission. We also considered overlap with Optical goals. This section of the report summarizes the detector technologies and lays out the methodology by which some technologies were deemed most promising for making an impact for future discoveries. A brief description of the detector technologies, their advantages, and an estimated time and cost of their development is included in this part of the report and in Appendix VIII.

Members of the Detector Breakout Group are listed below:

The Detector Breakout Group Members: Michael Hoenk (Chair), Tim Goodsall (post doc), Todd Veach (student), Sam Cheng (student), Edoardo Charbon (KISSUV DVS), Liz Nanver, Ossy Siegmund, Bruce Woodgate (present in workshop 1), Kris Bertness (present in workshop 1), Shadi Shaedipour, Shouleh Nikzad, Alice Reinheimer (e2v Aerospace and Defense), Ben Mazin, Patrick Morrissey, Chris Martin, Paul and Scowen.

Table 3 — New UV Detector Developments Enable New Measurement Capabilities Required for Future Missions [See Table 4]

UV Detector Property	UV High Resolution/High Contrast Imaging	UV Wide Field Imaging	UV High Resolution Spectroscopy	UV Multi-Object Spectroscopy	UV Integral Field Spectroscopy	Current Performance
QE	Moderate	Moderate	High-Very High	High	High-Very High	Low-Very Low
Format: Number of Pixels	Very High	Very High	High-Very High	High-Very High	High-Very High	High
Photon-counting	XX	X	XXX	XX	XXX	YES
Equivalent background	Low	Moderate	Very Low	Low-Very Low	Very Low	Moderate
Dynamic Range	High	High	Moderate	Moderate	Moderate	Moderate
Radiation Tolerance	Moderate	Moderate	Moderate	Moderate	Moderate	High
Time Resolution	Low	Low	Low	Low	Low	High
Out of Band Rejection	High	High	Moderate	Moderate	Moderate	High

4.2 Background: UV Detector Technology

Ultraviolet detectors can be classified into two major categories: 1) Vacuum tube technologies that combine an ultraviolet sensitive photocathode, e.g., CsI or CsTe, with a gain component, and an electron detector. In these imagers, a photocathode is used to convert UV photons into electrons, which are subsequently amplified through a gain mechanism and detected. Microchannel plates (MCPs) and electron bombarded CCDs (EBCCDs) are in this first category of UV detectors. Efficiency, reliability, and complexity (in fabrication and operation) of the imagers greatly depend on the properties of their photocathodes. 2) Solid-state devices based on silicon or wide bandgap semiconductors.

Solid-state detectors have long held the advantage in high UV quantum efficiency over their photocathode-based counterparts, the electron-multiplication gain component built into vacuum tube based detector technologies enables high signal to noise ratio and therefore single-photon counting detection. Despite the low QE of photocathodes, the capability for single-photon counting enables higher signal-to-noise detection at very low light levels than conventional solid state detectors with high quantum efficiency and 1-2 e^- read noise. Until recently, this was the state-of-the-art. In 1997, for example, the NASA GALEX UV sky survey mission. Recent advances in UV detector technologies have enabled laboratory demonstrations of single-photon detection with solid-state detectors on the one hand, and higher-quantum efficiency photocathodes for microchannel plate detectors on the other. As detectors were identified as high impact technology, a goal of this study was to identify which of these potentially mission-enabling UV detector technologies, with a relatively small investment by KISS in further development, would have the greatest impact on astrophysics and planetary exploration. Thus, in addition to their enabling capabilities, the relevant technologies are evaluated based on estimated time and cost to achieve readiness for spaceflight. Mission-enabling detector technologies worthy of further investment are described on the following pages.

4.3 Vacuum Tube Photoelectric Detectors

Traditionally, for space and laboratory applications, MCPs have been chosen because of their photon counting capability and versatility. There is a long history (over 200 space-flight years) of experience with MCP UV detectors. On the other hand, these devices have relatively low UV quantum efficiency (~5-20%) due to the photocathode QE, require high voltage power supplies, and often need sealed tube encapsulation to preserve the photocathode. Fabrication of microchannel plates with reliable properties has been historically challenging, and usual employ glasses that have a significant residual radioactivity induced dark background. Dynamic range has been limited in the past. Significant efforts are underway to change the MCP paradigm and improve quantum efficiency, dynamic range, and dark background, as we discuss below.

Table 4 — UV Detector Technology Performance Definitions [see Table 3]

UV DETECTOR PROPERTY	Very Low	Low	Moderate / X	High / XX	Very High / XXX
QE	>5%	>15%	>30%	>50%	>70%
Format: Number of Pixels	100 x 100 10^4	300 x 300 10^5	$10^3 \times 10^3$ 10^6	$(3000)^2$ 10^7	$(10,000)^2$ 10^8
Photon-counting		Not important	Important	Very Important	Critical
Equivalent background [ct cm ⁻² s ⁻¹]	0.01	0.1	1.0	10	100
Dynamic Range [ct/s]	$10^{-3}:10^0$	$10^{-3}:10^1$	$10^{-3}:10^2$	$10^{-3}:10^3$	$10^{-3}:10^5$
Radiation Toler.		1 kRad	10 kRad	100 kRad	1000 kRad
Time Resolution	None	1000 s	1 s	1 msec	1 usec
Out of Band Reject.	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}

4.3.1 Generation-2 MCP Detectors: Borosilicate/ALD/GaN MCPs

MCP electron imaging amplifiers were introduced in the early 1960s as an outgrowth of work on single channel continuous dynode multipliers, and have since become a mainstay of many classes of imaging system. Initially used as an element in image intensifiers, the MCPs direct sensitivity to electrons, ions, and x-rays have resulted in an enormous range of applications, from UV astronomy to electron spectroscopy. The pore sizes used today range from 2 to 25 microns, with 6 to 10 microns a more typical range in astronomy. The channel length to pore size ratio is typically in the range 40 – 120:1 and sizes of ~100 mm diameter are available. Single plates have an electron gain typically in the range 10^3 - 10^4 . In order to achieve higher gains, MCPs are often used in a stacked configuration of two ("chevron") or three ("Z stack") parallel plates in close proximity, with opposing bias angles. Gains of $>10^7$ are then readily achieved. In addition to these useful characteristics, MCPs also have: the capability to match a focal surface using a curved MCP, room temperature operation, radiation hardness and bandpass selectivity (e.g. solar blindness).

Many electronic imaging array detectors use MCPs as a photoelectron amplifier in front of a two dimensional patterned anode such as a cross delayline, cross strip (medipix, timepix). Each readout technique is optimized for the particular imaging science required (e.g. high spatial and temporal resolution, very high rate, low gain, high dynamic range etc.). Over the last twenty five years, these readouts have improved their spatial resolution by a factor of 10, their count rates by a factor of 1000, and the corresponding gain required to achieve high resolution has decreased by a factor of ~100. MCP detectors can now reach spatial resolutions of $<10\mu\text{m}$ FWHM, photon counting rates of many MHz, and lifetimes of 10^{10} events/mm² [Martin 2003]. Over the same

period, parameters strictly limited by the MCP itself, such as area, pore size, gain, and lifetime (as measured in Coulombs/mm²) have, only improved by a factors of ~ 2, and are a major cost element for large (>7 x 7cm) areas.

A potentially substantial improvement in MCP performance, scope and robustness for astronomical applications using the technique of ALD onto borosilicate glass substrates to make a new generation of microchannel plates. The MCPs are based on a novel concept where the substrate is constructed from a borosilicate (700°C softening point) micro- capillary array that is made to function as an MCP by deposition of resistive and secondary emissive layers using ALD [Leskelä 2003, Mane 2011]. This differs from conventional MCP lead glass construction [Lampton 1981], removing the need for chemical etching and H₂ reduction steps, allowing the operational parameters to be set by tailoring the sequential ALD deposition processes. The process is relatively inexpensive compared with conventional MCPs and allows very large MCPs to be produced with pore sizes in the 40 μm to 10 μm range, and open areas up to 85% rather than ~60% for conventional MCPs. Initial work has already been done [Siegmond 2011] with smaller test MCPs which shows they provide many performance characteristics typical of conventional MCPs, and they have now been made in sizes up to 20 cm, have low intrinsic background (0.085 events cm⁻² s⁻¹) and very stable gain behavior for at least 2.5 C cm⁻² of charge extraction.

The photon sensitivity (QE) of MCP detectors is determined by the photocathode choice and the detection of the photoelectron by the MCP [Siegmond 1998] for further amplification. Opaque photocathodes, which we usually directly deposit on the MCP tend to have a higher QE than proximity focused semitransparent mode cathodes deposited on a window directly in front of the MCP. However, current MCP technologies are not compatible with direct deposition of some potentially new high performance photocathodes (GaN) on their surfaces, both chemically and thermally, as the deposition temperatures can be too high for the current MCP glass or the composition incompatible. Though the QE is largely determined by the interplay of the absorption coefficient of the photocathode and the photoelectron escape length, the probability of detecting the first photoelectron by the MCP is also very important. The open area ratio of the pores and the secondary electron emission coefficient vs. input electron energy both affect the detection quantum efficiency of the detector as a whole. Typical opaque cathodes for <200nm are alkali halides with up to 65% QE (<115nm), and up to 50% (>115nm) with cutoffs ~190nm. Opaque and semitransparent cathodes used for 200nm to 300nm have <15% QE, while semitransparent cathodes for 300nm – 900nm have peak efficiencies of ~25%.

The ALD-borosilicate MCPs offer a potentially cleaner, more robust (700°C softening point) and tolerant substrate for opaque photocathode materials. We have begun investigating this opportunity by depositing opaque GaN (p-doped, Cs activated) photocathode onto an ALD borosilicate MCP (NiCr surface) by molecular beam epitaxy. The value of QE values achieved are about half the QE obtained for opaque GaN photocathodes epitaxially grown on lattice matched sapphire (Al₂O₃) substrates that we have measured previously [Siegmond 2008]. The latter give QEs as high as 80% at wavelengths of 120nm and a cutoff at ~360nm. However, it is significant that a high level of efficiency has been achieved on a non-optimal substrate and

without a Cs deposition optimization process. Immediate improvements are potentially possible by optimizing the GaN deposition process, including the provision of an Al₂O₃ layer deposited onto the MCP by ALD [Mane 2011].

The possibility of using this type of ALD borosilicate MCP/photocathode to satisfy potential future applications for NASA Astrophysics has many advantages. Provided that MCPs with small pores (10 μ m) can be developed, and functionalized with ALD, this technique could provide very large (20 x 20cm) area MCPs with high spatial resolution (<20 μ m), low in-orbit background rates (<0.05 events cm⁻² sec⁻¹), better robustness (gain stable to >10¹² events/mm²) and compatibility with new photocathode technologies (GaN, etc), and at a fraction of the cost (\div 10) of conventional MCPs. Other potential fields impacted by this work include homeland security applications (large area radiation monitoring), biology (fluorescence imaging/timing), mass spectroscopy, high energy physics (Cherenkov imaging/timing), and materials research (high time resolution imaging photoelectron spectroscopy).

4.3.2 Advanced Electron Bombardment Arrays

Electron bombarded CCDs (EBCCDs) and microchannel plates (MCPs), which use photocathodes to convert UV photons to electrons, are in the first category of UV detection technology. Electron-bombarded arrays potentially have the highest QE in the FUV since they exploit opaque photocathodes. This however requires the photoelectron to be ejected back into the direction of the input optical beam. In order to image the photoelectron accurately and produce a large electron signal in the CCD, a high voltage and large permanent focusing magnetic field is applied. While excellent in certain applications (flight-proven on the IMAPS instrument), the detectors tend to be bulky, and it may be difficult to design opaque EBCCD detectors for instruments requiring fast optical beams or large formats.

Advances in compactness, quantum efficiency, and ease of manufacturing will make these high performance devices more attractive for flight. Delta doping (see below) of the back illuminated CCD or CMOS array improves the low energy electron detection threshold of the device dramatically allowing the reduction of the acceleration voltage and reduction of size and complexity of the detector. Readout schemes for this device that will not require bending the electrons from the line of sight of the detector and treats the visible-generated electrons as a source of noise that can be discriminated, have been devised. No high voltage requirement and removal of the bending magnet can greatly simplify and reduce the size of new EB Arrays while maintaining the high efficiency and visible rejection advantages.

4.3.3 Cs free GaN photocathode

GaN and AlGa_N based photocathodes have attracted considerable attention for their application in image intensifiers, astronomy and UV detection and emission systems. Small electron affinity of AlGa_N alloy allows development of high quantum efficiency negative electron affinity (NEA) photocathodes with significant advantages such as solar blindness, radiation hardness and low noise. Conventional photocathodes achieve NEA by cesiating the photocathode surface. Fabrication, optimization, and installation in vacuum is required for cesiated photocathodes due

to the high chemical activity of the Cesium. Such requirement increases cost and limits the range of potential applications. Further, such photocathodes have been reported to suffer from chemical instability and degradation with time. *Recent reports made by the UAlbany-CNSE/JPL group have shown the potential of a novel Cs-free GaN based photocathode that utilizes band engineering near the photocathode surface to achieve permanent NEA.* Device structure is composed of a Mg doped GaN grown on sapphire substrate, followed by Si-delta doping and a thin n^+ GaN cap. By placing a Si delta doped layer on the Mg doped GaN surface conduction band of the overall structure is pulled close to the Fermi level of the p-GaN. A thin n^+ GaN cap is deposited to provide stability to the Si-delta doped layer. Device design parameters including Si-delta doping and thickness of n^+ GaN cap layers play a critical role in determining the emission threshold and quantum efficiency of the device. Further, polarization induced charges at the device surface influence the device characteristics. We have performed physics based simulations to optimize the device design parameters taking into account polarization induced surface charges. Device structures have then been epitaxially grown using a Veeco D180 MOCVD system and characterized using secondary ion mass spectroscopy (SIMS) and photoemission (PE) measurements. A series of growth experiments with varying conditions have been performed to optimize Si incorporation in the delta doped layer and quality and thickness of the n^+ GaN cap layer. Emission threshold of the device has been observed to increase with increase in the n^+ GaN cap thickness. Such behavior has been successfully modeled and is attributed to local electric fields caused by the negative polarization induced surface charges. Quantum efficiency of the device follows systematic exponential decay with increase in n^+ GaN cap thickness. Increase in Si incorporation in the delta doped layer, up to the optimum value, has shown to improve device characteristics. Further increase in Si incorporation caused increase in emission threshold and degradation of the photocathode surface.

4.4 Solid-State Detectors

Solid-state detectors, on the other hand, offer significant advantages in size, mass, power, reliability and manufacturability compared to the vacuum tube based technology of MCPs. To surpass the performance of MCPs and enable major new scientific impacts, what is required is a solid-state UV detector with stable, high QE, low noise, and moderate gain. Solid-state detector arrays with these capabilities would fulfill the need for instrument compactness and reduction of instrument complexity, both of which are at a premium especially in instruments designed and built for space (especially for in situ instruments) and biomedical applications.

4.4.1 Solid-State Wide Bandgap Detectors

Wide bandgap materials such as gallium nitride (GaN) are intrinsically insensitive to visible photons and these materials are being exploited for UV detector arrays as well as UV photocathodes. For UV detector arrays, a multilayer structure of GaN or its alloys is grown by a technique such as MOCVD or MBE on a sapphire substrate. An array of p-i-n diodes is then fabricated from this material and hybridized to a CMOS readout array. There has also been report of success with wide band gap avalanche photodiode arrays possessing gain. These detectors still suffer from higher defect density, higher noise, and poor uniformity due to materials issues.

AlGaN Avalanche Photodetector (array): The III-nitrides are physically and chemically robust, can be doped both n and p type, and have been shown to achieve high QE as photo-detectors, detector arrays, and photocathodes. These are among the attributes that make III-nitride materials nearly ideal for detectors with gain, i.e., APD designs. An AlGaN UV detector operating at 325 nm gives a 1000× better extraterrestrial solar radiation rejection than silicon. This reduced need for blocking filters increases the overall quantum efficiency (QE) and simplifies the optical systems. The wide direct bandgap reduces the thermally generated dark current to levels that allow many observations at room temperature. Because of this, the AlGaN UV photodiode array doesn't require the extensive cooling (and the associated cooling cost, complexity, and weight) that silicon does, significantly reducing system cost. Wide direct bandgap materials are naturally more radiation tolerant, which is crucial for instruments located outside of Earth's atmosphere.

Several materials challenges have stood in the way of producing high quality AlGaN APD structures that can be integrated with Si CMOS readouts. The key issue in large part is the high density of dislocation defects due to the large lattice mismatch between the III-nitride layer and the commonly used substrates (e.g. Sapphire, SiC, Si).

Solar blind Schottky, p-i-n, and simple Metal Semiconductor Metal (MSM) photodetectors with excellent detectivities have been reported in the last several years. Only a few GaN-based APDs have been reported in the literature. Geiger-mode operation has been demonstrated in GaN with a peak response at 362 nm corresponding to the GaN bandgap and linear-mode operation has been demonstrated in $\text{Al}_{0.38}\text{Ga}_{0.62}\text{N}$ with a peak response at 278 nm. These initial demonstrations are very promising, and indicate that with improvements in the material quality and device design GaN-based APD arrays are within reach. However, several problems must be addressed to achieve this goal. For example, yields were very low in the GaN APD devices due to defect-related micro-plasmas in the material. Yields have not yet been reported for AlGaN-based devices. Larger devices show very high dark current which is direct evidence of the effect of defects in the material rather than processing-related defects. As was shown previously in GaN-based APDs and now in AlGaN Solar-blind APDs, material quality is the major issue in achieving high efficiency APDs. GaN based APD structure on bulk GaN substrate with defect density in the 10^7 cm^{-2} is demonstrated to have three order of magnitude lower dark current as compared to similar structure on lattice mismatched sapphire substrate. *The UAlbany-CNSE/JPL team has recently demonstrated avalanche action in GaN pin device structure with a gain of 80K at a bias of 85V for a 40 μm device.* This was mainly achieved by passivation of surface states. It is expected that improvement in p-layer conductivity, higher quality material (lower defect density), along with novel device structure design (SAM design, confined multiplication region, and back-illumination) will result in >one order of magnitude in dark current directly translating into higher quantum efficiency, and higher gain at lower voltages.

Multiple groups have demonstrated focal plane imager based on AlGaN p-i-n photodiodes. In array format, a rejection ratio of greater than three order-of-magnitude is observed before and after the cutoff edge (365nm for GaN pin). In one report for a large format array, the QE is seen

to fall rapidly with decreasing wavelength reaching a minimum of 3 percent at 345 nm. [Shahid Aslam and David Franz of Goddard Space Flight Center, 2010]. The detector's current responsivity at 360 nm and 0 V bias is 0.13 A/W. The spectral detectivity is 2.6×10^{15} cm Hz^{1/2}W⁻¹, corresponding to a detector noise equivalent power of 4.1×10^{-18} W/Hz^{1/2}.

4.4.2 UV Single Photon Counting Silicon Detectors

An immense investment has been made in order to produce silicon detectors with very low noise, low dark current, and very large imager formats. Significantly, silicon sensors have now become viable for photon counting applications using new architectures to achieve gain, such as Electron Multiplied Charge-Coupled Devices (EMCCDs) with lateral gain, CMOS sensors with in-pixel avalanche photodiodes, and ultralow noise CMOS arrays (0.7 e- read noise) as described below. While silicon array detectors offer enormous advantages, their application to UV detection historically has posed four challenges: 1) achieving high and stable QE, 2) developing a suitable gain mechanism for photon-counting operation, 3) mitigating out-of-band (red) sensitivity, and 4) mitigating radiation damage.

4.4.2.1 High and Stable UV QE in Silicon Detectors

Because of the shallow absorption length of UV photons in silicon, the conventional front-illuminated configuration of silicon photodetectors is not suitable for UV detection. UV silicon detectors must instead be operated in a thinned, back-illuminated configuration, in which photons are incident on the bare silicon surface opposite from the circuitry. While back illumination enables UV detection by avoiding absorption and scattering in front-surface gate and pixel structures, back-illuminated silicon arrays have historically suffered from instabilities related to the Si-SiO₂ interface created by the substrate-removal process. Thus, back-illuminated silicon detectors require effective methods of surface passivation to achieve high, stable quantum efficiency, especially in the ultraviolet, where UV absorption in the passivating layer can also play a limiting role in detector spectral range and stability. Without effective surface passivation, traps at the Si-SiO₂ interface can dynamically interact with photo-generated charge, resulting in poor quantum efficiency, unstable response (quantum efficiency hysteresis), and high dark current. Various surface passivation methods have been developed for back-illuminated detectors in order to improve the UV response, reduce surface-generated dark current, and stabilize the overall quantum efficiency. Ion implantation techniques and chemisorption techniques applied to thinned backside-illuminated charge-coupled devices (CCDs) have achieved high quantum efficiencies in the near ultraviolet region of the spectrum (above 250 nm). Extending these techniques to detect shorter wavelength photons, these detectors encounter instability and low QE.

Delta doping technology, developed at JPL, using molecular beam epitaxy (MBE) uniquely achieves atomic-scale control over the surface bandstructure of a silicon imaging array, resulting in near-100% internal quantum efficiency from the EUV through near infrared regions of the spectrum, very low surface-generated dark current, and elimination of quantum efficiency hysteresis. Delta doping is versatile and compatible with fabrication at foundries and it can be applied to practically any fully fabricated silicon array. This has been demonstrated by its application to various CCD designs and formats, CMOS arrays, PIN diode arrays.

Pure B technology for enabling UV detection: This passivation technique for back illuminated silicon arrays is more recently developed at TU Delft. In this approach, PureB layers are deposited from diborane (B_2H_6) at 700 °C and the thickness is well controlled down to a nanometer by varying the deposition time. Further reduction of the deposition time to achieve a thinner PureB coating can result in an uneven coverage of the Si surface that would finally affect properties. Although the technique is relatively new, encouraging results have been achieved on diodes and diode arrays in high UV efficiency. However, because of the high temperature that is necessary for this process, the technique cannot be applied to fully processed devices such as CCDs or standard CMOS.

AR Coating. Extending high silicon detector QE performance into the UV (especially 100-300nm) requires expanding the AR coating materials set and coating precision. The index of refraction of silicon is a strong function of wavelength especially in the UV, and certain materials (in particular hafnium oxide) that are ideal AR coatings from 240-300 nm, start to strongly absorb at shorter wavelengths. At shorter wavelengths, very thin films of materials such as magnesium fluoride and aluminum oxide behave extremely well. Atomically precise and reproducible AR coatings are required at these wavelengths. This is because changes in thickness of 2 nm or less can cause significant shifts in the peak AR response.

ALD is a precision technique, perfectly suited to these materials challenges posed in the construction of UV instrumentation. ALD is a thin film deposition technique similar to Chemical Vapor Deposition where a desired film is grown using sequential surface reactions, one monolayer at a time. The properties inherent to the ALD method enable growth of smooth, dense, pinhole free films with angstrom level thickness control over arbitrarily large surface areas. ALD is also well-suited for the growth of multilayer stacks of films with sharp interfaces. The technique is extremely flexible, with nearly every element in the periodic table accessible as an ALD material. As ALD inherently enables careful control of interfaces, it is sufficiently gentle to allow multilayer ALD films of a variety of materials to be directly grown onto a detector, such as a silicon CCD, to fabricate a simple, compact detector that has the highest possible sensitivity.

4.4.2.2 Photon-Counting Silicon Detectors

4.4.2.2.1 Electron-multiplied CCDs (EMCCDs)

Electron-multiplied CCDs (EMCCDs) developed in two different design by E2v and TI leverages all the advantages of the mature CCD technology while enabling single photon detection by adding a gain register after the serial register of the CCD (at the end of the charge transfer) prior to the readout amplifier. At each stage of this gain serial shift register, a higher gate voltage in the second serial clock phase (~40V) causes avalanche effect. The avalanche effect produces a small gain in each charge transfer, which results in a final gain of more than one thousand. Single electron signals are amplified far above the read noise floor and read out through a discriminator, effectively eliminating read noise. EMCCDs can operate with a range of gain from 1000 (photon-counting) to 1 (conventional CCD) and can therefore accommodate a wide dynamic range of signal. Faint spectroscopic observations can be observed in full photon

counting mode at high gain through a discriminator, *and because of the low counts per pixel suffers no root 2 multiplication noise penalty*. Bright targets are observable in conventional (no amplification) mode. A small subset of intermediate brightness targets can be observed at moderate gain with root 2 multiplication noise.

4.4.2.2.2 Single Photon Avalanche Photodiode Diodes (SPADs)

Single Photon Avalanche Photodiode Diodes (SPADs)--- An optical or UV SPAD is a reverse-biased pn junction operating in Geiger mode, so as to detect single photons; it is also known as Geiger-mode avalanche photodiode (GAPD). A CMOS SPAD is a SPAD implemented in a CMOS process; it can operate in frontside illumination (FSI) and backside illumination (BSI) regimes; in the latter regime a substrate thinning and surface processing techniques, such as PureB or delta-doping, are required for UV detection. Upon detection of a photon, SPADs generate a digital signal that is fully CMOS compatible; it can be used by further digital processing on- or off-chip.

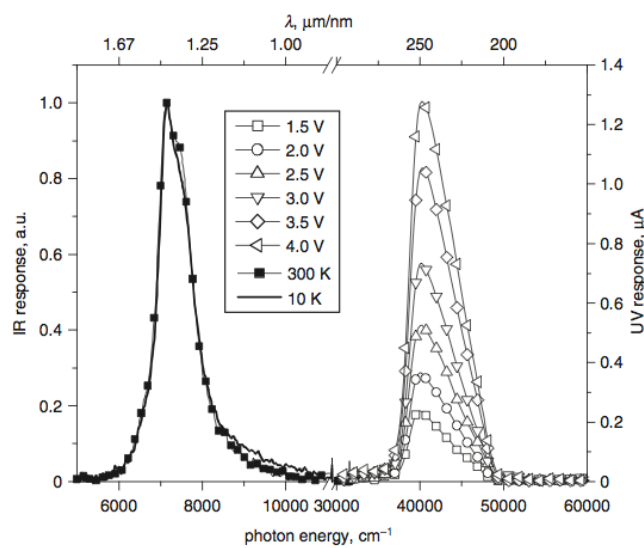
4.4.2.2.3 Hybrid APD-CMOS ROIC

Figer-MITLL: Linear Mode (LM) and Geiger Mode (GM)

In a hybrid approach different technologies, processed independently, can be combined into one chip. Many ways of doing this are being explored for a multitude of electronic, photonic and optoelectronic applications. Specifically for APDs the aim has been to increase the fill-factor and responsivity for megapixel imagers. Originally reported technologies for achieving this include joining foundry chips by bump bonding or epoxy bonding the APDs to foundry chips, which delivered coarse (100 μ m) pixel spacing and 0.5 ns timing quantization. More recently Lincoln Laboratory has demonstrated a fully depleted SOI CMOS fabrication process and techniques to fabricate three-dimensional integrated circuits by stacking SOI wafers to form multiple “tiers” of circuitry interconnected with micron-scale vias. Such a 3D integration process could enable new computing architectures that exploit short, massively parallel interconnections between tiers. They presented a 3D-integrated 3-tier 64 \times 64 ladar focal plane with 50 μ m pixel spacing and circuitry added to the pixel to refine the timing quantization. Timing quantizations of 130ps and 110ps are obtained, respectively, for the rising and falling clock edges. Power distribution issues and a readout clock race condition constrained operation to a timing resolution of 2 ns.

4.4.2.2.4 Quantum Cascade Detectors

This concept was proposed by Edoardo Charbon at one of the brainstorming sessions in the first workshop. Quantum cascade detectors (QCDs) are an emerging technology that is showing promise in single-photon detection at a large range of wavelengths from UV, visible, to NIR. The main advantages of this technology are selectivity, compactness, and GaN compatibility. The figure below shows a typical response observed in a QCD detector as a function of wavelength [Hofstetter08].



The structure of the QCD we propose to implement is based on a series of thin films of AlGaIn and/or a AlN/GaN superlattice [Hofstetter03] to achieve, for example, a dual band detection. A feedback amplifier (either external or integrated) with programmable gain and bandwidth should be added in this setup to ensure the proper functionality. These films can be grown by plasma-assisted molecular-beam epitaxy on a commercial AlN-on-sapphire or other appropriate substrates. Responsivities of 10mA/W are expected in a 250nm to 350nm wavelength range.

4.4.2.3 Out-of-band response

A part of any UV detector concept is the consideration of its sensitivity to visible light photons, also known as the “red leak.” During the workshop we reassessed the requirement that a detector technology be “solar blind,” often levied as a stringent out-of-band rejection specification. This requirement is based on the red spectra of certain classes of (astrophysical objects and also considers the contribution from foregrounds and backgrounds, including the zodiacal light, which has the spectrum of reflected sunlight. While some of these red objects produce millions of visible photons for every UV photon ($F_{UV}/F_{vis} < 10^{-6}$) it is also the case that many of the objects studied in the UV have much more modest visible rejection requirements with ($F_{UV}/F_{vis} < 10^{-3}$). Nearly all of the objects *actually detected* by the GALEX mission have UV optical colors, $NUV-r < 7.5$, consistent with the latter, less stringent specification. As we move towards astrophysical investigations of very faint and/or diffuse objects, observations will often be made in the sky background-limited regime. While zodiacal light contributes to the diffuse sky background, the contribution from diffuse Galactic light is significant in the UV, and therefore $I_{UV,sky}/I_{vis,sky} > 10^{-2}$ again suggesting relatively modest red rejection requirements for in-band, background-limited performance. Very cool and/or dusty objects, including planetary and exoplanet observations can present more severe out-of-band rejection requirements; inevitably the relative priority of this requirement will need to be made depending on the specific requirements of a mission. In fact, some detectors with significant out of band rejection (e.g. with CsTe photocathodes) still show sensitivity to visible light and may require additional blocking, as was done with the red blocking filter on GALEX.

Silicon-based technology is sensitive to visible photons but its incorporation in a spectrograph can achieve the in-band, background-limited performance required for many investigations. Historically, missions have utilized detectors with sensitivity that extends into the UV on general-purpose instrumentation operating in the visible. This has been done on HST/WFPC2, ACS/HRC, WFC3/UVIS, XMM/OMM, SWIFT/OMM despite the potential for out of band light that may impact observations of very red objects. These are all active instruments that done exceptional science. At this workshop we also discussed new approaches for achieving enhanced visible rejection using in situ filters (cf. Section 4). Although these are challenging, requiring rejection of visible photons without sacrificing in-band UV performance, they are an interesting area of research.

4.4.2.4 Radiation Mitigation

Radiation exposure produces electron traps that reduce charge transfer efficiency and increase dark background. The community has gained considerable experience managing radiation effects in space-borne CCD detectors. EMCCD gain registers have been tested at robust radiation doses comparable to at least 10 times typical LEO lifetime exposure. Custom EMCCDs can be designed tailored to reduce radiation effects (e.g. notching), permit successful transfer of low charge levels (even 1 electron) over the full CCD array, and minimize significant radiation-induced dark background enhancement.

4.4.2.5 The Promise of High QE Photon-Counting Silicon Detectors

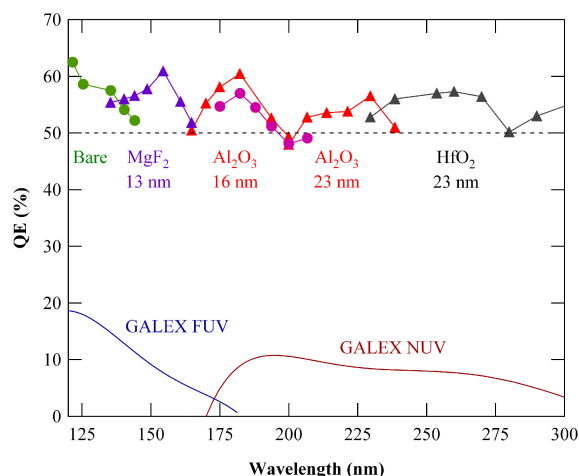


Figure 3 Very high QE has been demonstrated for Silicon CCD detectors over the 120-300 nm UV range. High QE is obtained using delta-doping and ALD AR coating tuned to various bands

A new high efficiency solid-state single photon counting UV detector array combines the nano-engineered surface passivation and AR coating using MBE and ALD with electron multiplication S/N advantage of low noise and avalanche gain in a Delta doped ALD deposited AR coating EMCCD. The combination of the MBE for delta doping and ALD AR coatings provide atomic-scale control over interface properties to achieve high and stable QE. Delta doping has been achieved on EMCCDs designed and fabricated by e2v and has been demonstrated to achieve reflection limited response on e2v's L3CCDs. Delta doping has been shown to achieve reflection-limited response in silicon detector arrays. To achieve higher QE, AR coatings must be applied to this challenging part of UV spectrum. The challenge of developing AR coatings

for this spectral range (*i.e.*, 100-300 nm region) include a rapidly changing index of refraction, material limitations for having both low absorption and high index, constraints on deposition methods that at once offer high quality ultrathin layers without affecting the delta doped layer or the front-side collection and readout circuitry of the device. Single layer AR coatings have been applied to delta doped CCDs (not all EMCCDs) and at proof of concept level have shown dramatic increase in the QE to above 50% in the 100-300 nm range

4.4.2.6 Curved Solid State Detector Arrays

Curved focal plane arrays (CFPAs) enable significant miniaturization and improvement of optical systems that will enable NASA to achieve its scientific objectives in future missions. In most optical systems the focal surface is naturally curved, while most detector arrays are flat. While other aberrations depend on the stop and conjugate positions within an optical system, field curvature generally depends only on the basic constructional parameters of the system and the throughput. It is thus very difficult to change, and can be regarded as intrinsic to an optical system [Mouroulis and Macdonald, 1997]. The designer has more degrees of freedom in controlling other aberrations than in controlling field curvature. Curved focal planes offer a way out of this dilemma by permitting the designer to concentrate on the correction of other aberrations rather than having to abandon a certain design approach due to excessive field curvature [Mouroulis03]. One study showed that allowing a curved focal surface in optical design enables critical improvement in wide field imaging systems. Using such innovation, an instrument having the capabilities of the Multiangle Imaging SpectroRadiometer (MISR), which was built to monitor the Earth's climate using simultaneous multi-angle imaging, could be miniaturized from the size of an office desk to the size of a suitcase.

Curved detector arrays have been implemented in the form of curved microchannel plates (MCPs). The first curved MCPs were critical to the NASA (Far Ultraviolet Spectrometer Explorer (FUSE) mission and the Alice instrument in Rosetta. Solid-state CFPAs potentially offer higher efficiency, higher resolution, higher dynamic range, wider spectral range, much lower power requirements, and they eliminate the need for high voltages. Delta doped arrays have been made into curved surfaces (spherical) at the proof of concept level. The proof-of-concept results have shown that the detector is functional, robust, and has retained its response without any adverse effects on dark current or responsivity.

4.5 Cryogenic Detectors

Cryogenic detectors are currently the preferred technology for astronomical observations over most of the electromagnetic spectrum, notably in the far infrared through millimeter (0.1– 3 mm), X-ray, and gamma-ray wavelengths ranges.

Superconducting Tunnel Junctions (STJs) and Transition Edge Sensors (TESs). While both of these technologies produced functional detectors, they are limited to single pixels or small arrays due to the lack of a credible strategy for wiring and multiplexing large numbers of detectors, although recently there have been proposals for larger TES multiplexers.

Microwave Kinetic Inductance Detectors, or MKIDs, are an alternative cryogenic detector technology that has proven important for millimeter wave astrophysics due to their sensitivity and the ease with which they can be multiplexed into large arrays. MKIDs use frequency domain multiplexing that allows thousands of pixels to be read out over a single microwave cable

4.6 Detectors for UV/Optical/NIR Observations

One of the productive and animated discussions during our workshop revolved around UV only observations versus UV/Optical. The merits of combining the two ranges rendered exciting science possibilities such as exo-planet atmospheric analysis. More of this discussion is covered in the science part of the report but here we cover the detectors possibilities for this spectral range.

4.6.1 Broadband Detectors using Silicon

In the last ten years, detectors have been developed in high purity silicon substrates using essentially conventional designs with one exception on the full depletion. These detectors have the advantage that they can be used from UV (when delta doped) to NIR (about 1 μm , as far as silicon bandgap allows). This has the advantage of being used in a dichroic system with two channels with essentially identical cameras except for the AR coatings that cover the imaging array for the blue or red channels.

4.6.2 Broadband Detectors using substrate removed Mercury Cadmium Telluride

Mercury Cadmium Telluride (MCT) detectors are often used for short and medium wavelength infrared observations. More recently, it has been shown that the removal of the CdZnTe substrate extends the response of these detectors into the blue region of the spectrum. This is attractive because near UV to IR detection can potentially be detected in one detector. Compared to silicon arrays, these detectors are more costly. It is also more challenging to produce large area arrays with good uniformity because of the ternary alloy epitaxial layers needed for the detector material. Preliminary measurements have shown UV response in these devices.

Because the bandgap is small, however, it is potentially possible to produce higher gain (quantum yield) distinguishing the UV photons. This is potentially an area of further investigation.

4.7 Summary and Recommendations

A number of detector technologies were discussed during the study. One of the most interesting, but perhaps controversial, activities of the detector study group was to apply figures of merit to the various technologies in order to better understand both their potential scientific impact and the projected time and cost to achieve their promise. Four principle areas were considered:

1. *Current and projected (2020) performance.* QE vs. wavelength, internal/dark noise, photon-counting capability, number of pixels/formats/scalability, energy resolution, dynamic range.

2. *Implementation and operational issues/risks*: e.g., requirements for cooling, high voltage, required materials/process improvements, red leak/out of band response.

3. *Cost/time to TRL-6 and leverage*: What is the current TRL level, what funding and time is required to reach TRL6, what is the degree of difficulty of these developments. What resources can be brought to bear to leverage the development (significant industrial involvement and prior investments, cross-division, cross-agency, private-sector investments and applications, existing infrastructure and institutional investment)

4. *Relevance to and impact on possible future missions*: How do the detectors fulfill the science measurement requirements described in §2. Some detectors may be “mission enabling”, and would represent the highest priority for immediate investment. Some technologies are “mission enhancing”. Some early investment should be considered contingent upon science and mission prioritization. Finally, many interesting and important technologies may be relevant to future UV missions. Some can be developed once mission choices are made. Others may be developed as part of other activities and programs. Still others may be at early stages of readiness and require more basic research support to mature.

Major detectors considered in this study:

- Back illuminated and delta doped Silicon arrays with gain
 - Electron multiplied CCDs
 - Single Photon Avalanche Diode Array (SPAD)—avalanche in CMOS pixel
 - Hybrid APD with CMOS readout (Figer-MITLL)
- Wide bandgap materials such as GaN/AlGaN photodiode arrays with avalanche gain
- Narrow bandgap materials such as HgCdTe (substrate removed and back-illuminated) and passivated for high QE in UV that enable gain due to higher quantum yield
- Microchannel plates with borosilicate material and ALD activation techniques and fitup with III-N photocathodes
 - III-N photocathodes (non-cesiated)
- Electron bombarded arrays with low voltage and III-N photocathodes
 - Use of delta doped silicon arrays for low energy e- detection and Low V operation
 - Non cesiated photocathodes
 - Delta doped CMOS arrays for low power and versatile readout
- Other categories such as curved arrays were also discussed as instrument enabling/enhancing technologies
- MKIDs

For each of the above detector technologies, a summary of description of the technology, advantages, and an estimated time/cost to develop are included in the appendix A VIII.

During both workshops and in the interim period, ideas and concepts were explored in more detail. Challenges associated with the development of each technology were identified and some plans or concepts were considered to address these challenges. For example, the dark rate associated with the SPAD technology was identified as a limitation that made the technology

unsuitable for most astrophysics applications. It should be noted that between the two workshops, the TU Delft group led by Prof. Charbon made an improvement by an order of magnitude. While this is a significant achievement, several orders of magnitude above usable floor remain. Some of the ideas considered to bring the dark current considerably down are fabrication of tunnel barriers using oxides. Some planetary UV instruments such as UV Raman spectroscopy can potentially use the time-resolved capability of SPAD to great advantage by distinguishing the fluorescence vs Raman.

Table 5 describes a summary of the more promising detector technologies based on impact and performance.

One of our study's principal conclusions was that UV detector performance drives every aspect of the scientific capability of future missions, and that two highly flexible detector technologies were at the tipping point for major breakthroughs. These are Gen-2 borosilicate ALD coated microchannel plate detectors with GaN photocathodes, and AR coated, delta-doped photon-counting CCD detectors. Both offer the potential for $QE > 50\%$ combined with large formats and pixel counts, low background, and sky-limited photon-counting performance over the 100-300 nm band. Ramped AR coatings for spectroscopic detectors could achieve QE 's as high as 80%

Table 5 — UV Detector Technologies [see color-coding in Table 4]

Type	Detector	QE			# Pixels (2012)	# Pixels (Projected 2020)	Photon counting	Dark Count Rate	Time Resolution	Out of Band	Energy Resolving	Photometric Accuracy/ Stability	Radiation Tolerance	Leverage	Implementation Issues
		DUV	FUV	NUV											
Photo-electric	BMCPs — opaque with CsTe	20-70	50-0	15+	1e7	1e7	Yes	2	3 μ sec	3	1	2	3	2	HV, sealed tube
	BMCPs — semi-transparent w/ alkali halide	—	35-0	8	1e7	1e7	Yes	2	3 μ sec	3	1	2	3	2	HV, sealed tube
	GaN+BSMCPs—opaque	no data	80-40	40-10*	1e7	1e8	Yes	2	3 μ sec	2	1	2	2	1	HV, sealed tube
	GaN+EBCCDs—opaque	no data	80-40*	40-10*	2e6	1e7		2	3 (1/60 sec)	2	1	2	2	1	HV, sealed tube
Super-conducting	MKIDs	30	>75##	>75##	1x64	1e6	Yes	3	3 μ sec	3	3?	3	2	2	Very cold, contamination, power, complex
Solid State Silicon	DD+AR+EMCCD	90-50	55#	55#	1.6e7 (buttable)	1e8	Yes	3*	2 (<1 sec)	1	1	Gain 1; Int 3	2	3	Cold, contamination
	SPAD-CMOS-Si (DD/B)	90-50			1e6		Yes	1	3	1	1	2?	3	3	Cold, contamination
	Si APD + CMOS ROIC	—	no data	55	6.5e4	1e6	Yes	1	3	1	1	2?	2	2	Cold, contamination
Solid State AlGaIn	AlGaIn APD	*	37**	37**	0	1e6	Yes	1—>?	3	2	1	2?	3?	2	Hybridization
	AlGaIn PIN	*	<45**	<45**	1e5	1e6	Yes	1—>?	1	2	2	2?	3?	1	

*Data for GaN PCs on sapphire substrates, not on MCPs; #Measured data, AR coating dependent; **Single pixel QE; ##Estimated based on absorption measurements of native film.

5 Discovery-Enabling New Optical Component Technologies

The deep (91-120 nm), far (120-200 nm) and near ultraviolet (200-320 nm) wave bands provide several unique challenges for optical component technology. These often lead to a trade-off between performance and feasibility and can impact design decisions at the earliest stages. New mission-enabling technologies have the potential to produce dramatic gains in performance and require the re-evaluation of workhorse technologies and conventional optical designs. As we discuss further below, in some cases these new advances may lead to astrophysical discovery not possible using currently existing technology.

The key design trade-offs for UV optical component technologies can be categorized in three broad areas:

- I. Dedicated UV vs. UV-Optical Instrument. Recent history has provided precedent for both types of instruments. The International Ultraviolet Explorer (IUE), the Far-Ultraviolet Spectroscopic Explorer (FUSE) and the Galaxy Evolution Explorer (GALEX) were all dedicated UV instruments with optical components optimized only for short wavelengths. The Hubble Space Telescope and the XMM and Swift UV/Optical Monitors require broadband UV/optical capability. In the case of HST, the fore telescope optics optimized for UV/Optical/NIR, are coupled to instruments that may in some cases be dedicated to a specific waveband. In the case of the optical monitors, all wavelengths traverse an identical path to the detector, with band selection accomplished using a transmissive filter wheel. Future mission concepts fall in both categories, with several facility-class designs (e.g. ATLAST, THEIA) exploring integrated and segregated UV-optical instrumentation. Proposals for a flagship UV/Optical mission generally seek an instrument with broadband fore-optic capability, as well
- II. Dedicated deep UV vs. Broadband UV Instrumentation: High efficiency deep UV instruments can be achieved with grazing incidence architectures using conventional optical coatings. However grazing incidence optics are more complex and costly to design and implement, particularly if one hopes to achieve optical PSF and wavefront performance comparable to that obtained with an equivalent aperture/focal-ratio normal incidence design. UV coatings allow implementation of normal incidence designs with excellent efficiency in the deep UV, though system throughput considerations may still limit the number of optical surfaces that may be used.
- III. Optical design performance and scalability vs. complexity and cost. Although this is coupled closely with I and II above, it includes the many other trade-offs that are not encompassed by the above systemic decision points. These include: higher reflectance mirrors that allow higher numbers of optical surfaces (degrees of freedom). Additional optical surfaces may also be required to achieve higher levels of multiplexing (e.g. integral field units); transmissive filters and components may on the other hand, reduce the number of required surfaces, and allow for more compact designs. Optical coatings, transmissive, reflective and blocking filters and diffraction gratings exist that provide adequate performance in conventional instrumentation, but it is well understood that

significant gains in throughput and sensitivity can be made owing to the multiplicative effect that coatings may have in a multi-mirror system.

Certain applications that employ new detector technology will simply not be feasible without advances in enabling technologies. Two examples are wide field imaging and photo-z surveys of large cosmic volumes, whether as part of transient searches or deep cosmology/evolution studies. Current silicon-based technologies such as CCDs have already achieved unprecedented pixel counts (0.1-1 Gigapixel) on the ground and in space (e.g. SDSS, Pan-STARRS, Dark Energy Camera, Kepler, GAIA). Super-wide-field UV surveys that would be able to exploit these available technologies would require blocking filters to eliminate red leak. Superconducting cryogenic devices such as MKIDs, designed to provide the highest 3-d pixel counting capability in a single detector, also require UV/optical-transmitting, IR blocking filters to prevent saturation. Red rejection even applies to photocathodes on microchannel plate detectors, for which the slow red roll-off may necessitate further band shaping that eliminates the visible but provides high throughput in the UV.

The enabling optical component technologies that were researched and developed in the KISS study were: 1) broadband coating designs and applications; 2) blocking and bandpass filters and 3) high performance diffraction gratings. The first of these is particularly relevant for UV vs. UV/Optical considerations. The latter two involve technology that will most likely be incorporated within a UV channel. The above technologies are briefly described below. Table 1 also lists several “blue” sky concepts that were explored, a number of which were considered to have potential worth following up in a low TRL study and/or small R&D projects.

5.1 Broadband coatings:

Reflective coatings in the UV have typically employed aluminum with a magnesium fluoride protective overcoat to prevent a highly absorbing oxide layer from building up on the Aluminum surface. Magnesium fluoride is highly transmitting throughout the UV but cuts off sharply below 120 nm. Lithium fluoride has been used instead, but it is hygroscopic with potential degradation that makes it hard to implement. At the shortest wavelengths silicon carbide and iridium has also been used, but with much lower reflectance. Aside from the short wavelength cut-off, magnesium fluoride layers can be tuned to optimize reflectance near a single wavelength, reflectance maxima peak near 90% though more typically reflectance between 85-90% is achieved. High performance coatings for excimer lasers, in some cases with additional dielectric multilayers, are now achieving better than 95-99% reflectance in selected wavebands on small optical components across the UV. Such performance gains applied to larger astronomical optics and multiple surfaces can enhance performance by 20-50%.

If UV reflective broadband coatings are to be used on a UV/optical instrument then they may also need to meet the requirements of the optical channel. Exoplanet science requires coatings of high reflectivity and minimal phase shift as a function of angle of incidence over the range 400-1100 nm.

Broadband transmissive coatings are mainly used as an anti-reflection coating and/or a protective coating for hygroscopic window/lens materials. As with broadband reflective coatings, these provide gains of a few percent per surface, with an impact that grows when additional optical components are added.

5.2 Bandpass/blocking filters

Unlike the broadband filters described above, conventional UV bandpass filters will typically require dielectric multilayer coatings. High index layers in particular are highly absorbing, limiting their use in transmission filters. Narrower high index layers improve performance at the cost of increased requirements for deposition thickness control and uniformity. Reflective bandpass and blocking filters can achieve good performance, although it is typically hard to incorporate these into compact optical designs. Bandpass filter requirements are application-specific (e.g. centered on key astrophysical emission lines or bands, line-free regions or absorption features). Reflective narrowband and dichroic/red-rejection filters have been designed and implemented using standard deposition techniques (electron beam with and without ion-assist, thermal evaporation). In general, these filters have never achieved theoretical performance because maintaining layer thickness control (e.g. ± 0.5 nm) and uniformity of film optical constants is challenging using these deposition techniques. With the availability of atomic layer deposition, the empirical limits of coating performance need to be re-evaluated, and new designs incorporating single atom nano-layers can now be implemented.

Band-edge and rejection filtering can also be achieved using bulk materials. Wire mesh filters (routinely used at IR wavelengths) and specially designed alkali metal filters (Woods' filter) have potential as short pass filters, although they have not achieved sufficiently high efficiencies to make them useful. Recent work on grid filters for the UV show promise, and further investigations are warranted.

5.3 High performance diffraction gratings

Nearly all dispersive elements fabricated for UV spectroscopic applications are reflective gratings generated using mechanical or holographic ruling techniques. (Prisms, grisms, and transmissive gratings have been fabricated, but limited material selection and low blaze efficiencies have resulted in limited use). Among the many challenges of UV reflective gratings are surface plasma effects at moderate groove density and surface-roughness induced scattering in low groove density echelle gratings. Groove control (e.g. curved, variable line spacing, patterned) can also provide gratings that enhance the performance of the optical system, in certain cases reducing the number of optics (or aspheres) and allowing designs that are compact and/or fast.

Electron-beam-fabricated gratings have the potential to be far more efficient, with lower scattering than conventionally ruled gratings. Photon-limited UV investigations that employ echelle gratings are often limited by the background from scattered light (whether from bright continuum, geocoronal Ly α , airglow or other bright emission lines) with an increasing dependence at short wavelengths. For example on HST/STIS, the fraction of light scattered into

interorder regions is 10-15% in the UV. Future observations can benefit from increased efficiency and higher signal to noise that an e-beam grating might provide.

A. Atomic Layer Deposition (ALD) is used to fabricate ultrathin and conformal thin film structures for many semiconductor and thin film device applications. ALD uses sequential self-limiting surface reactions to achieve control of film growth in the monolayer or sub-monolayer thickness regime. ALD has potential applications in advanced high-k gate oxides, capacitor dielectrics and diffusion barriers in advanced electronic devices.

A great strength of ALD is the conformality of deposited thin films over surfaces with extreme geometries. Precursor species are introduced into the reaction chamber individually, which allows deposition of complete monolayers before subsequent precursors are introduced. This differs from techniques such as chemical vapor deposition in which all precursors are present simultaneously. Thus the technique allows ultra-thin films of a few nanometers to be deposited with complete coverage in a precisely controlled way, and conformal coating can be achieved even in high aspect ratio and complex structures. In addition, a wide range of materials can be deposited with ALD.

ALD has only recently been applied to the development of single and multilayer optical coatings and filters. Precision control allows exploration of novel filter designs, taking advantage of increased layer control, uniformity of material properties, and unique combinations of material layers (e.g. graded index). Several members of the team have already begun this development.

B. Electron-beam lithography (e-beam) offers a promising alternative for UV grating fabrication. Precise surface profiling can be accomplished with feature sizes significantly smaller than the wavelength of light (depths appropriate for ultraviolet through long-wave infrared), and thus highly efficient diffraction gratings, diffractive lenses, and more exotic optics such as computer-generated holograms can be fabricated. Groove profiles can be made extremely smooth at the relevant spatial wavelengths, substantially reducing optical scattering, and arbitrary custom and multiple blazes can be accommodated. E-beam methods can also be used to add corrective figures to gratings in order to simplify instrument optics. The 3D resist profiles can be coated with metal for reflective applications, left uncoated for transparent applications, or transfer-etched into substrate materials for extreme environment applications.

E-beam lithography can be performed on *convex* and *concave* substrates as well. The need for non-flat gratings arises from compact, high-performance imaging spectrometer designs. Multi-blaze gratings can also be fabricated, composed of concentric areas that are blazed at different wavelengths. The blaze areas and wavelengths can be designed to tailor the spectral efficiency of the grating to compensate for poor detector sensitivity or illumination in certain regions of the spectrum. Additionally, the e-beam fabrication technique is so precise that it allows fabrication of *shaped-groove* gratings that utilize a single, computer-optimized groove shape that produces a tailored spectral diffraction efficiency that equalizes the signal-to-noise ratio of the spectrometer.

6 New Collaborations and Concepts Pursued

1. Improving energy resolved capability of UV/Optical MKIDs using bandstructure engineering with MBE. (Ben Mazin and Michael Hoenk).
2. Exploiting quantum yield of narrow bandgap materials for UV detection and visible distinction (Chris Martin, Shouleh Nikzad, and Mary Beth Kaiser).
3. Mission concepts on UV variability survey and ISS/Broadband (Matt Beasley and Hakeem Oluseyi)
4. ALD coatings for UV-visible range, with high reflectivity over the full range, and low phase-shift in the visible (Wes Traub, Frank Greer, and Shouleh Nikzad).

7 Conclusions and Recommendations

7.1 Potential Impacts

Our KISS Study identified portfolio of UV technologies that will enable and revolutionize the next generation of UV astrophysics, planetary, heliophysics, and earth-science missions. We developed ideas and identified and technologies with the highest scientific impact, that are near a tipping point in their development timeline, and that can be progressed with modest, targeted investments of funding from various sources. Because UV photons are absorbed at the very first few nanometers of the materials, nanotechnology tools and nano-engineered surfaces are the core of the most promising technologies. Some of the technologies have been demonstrated at some proof of concept and are ready for high payoff investment, while others are quite new and only at concept level. Some are completely new ideas that were invented at the KISS workshop. Table 1 summarizes key technologies ripe for investment, and the potential impacts on instrument and mission performance and affordability.

7.2 Recommendations/Conclusions

- Scientifically compelling medium-scale missions can be conceived assuming advances in UV technology.
- UV photon-counting detectors are ready for investment and an order-of-magnitude gain in performance.
- UV coatings using ALD could represent a breakthrough technology enabling broadband, high-reflectivity, high-performance optical designs, and a joint exoplanet/UV astrophysics mission.
- Modern nanofabrication technologies offer major new opportunities for developing novel UV detector, coating, filter, and diffractive elements.
- With modest advancements net gains of 10-1000 are possible by combining QE, background, field of view, and multiplexing advantages, even with moderate aperture missions.

Table 6: Mission Enabling UV Technologies

Technology	Implementation Approaches	Potential impacts	Mission Enabling Factor
SPUD: Single Photon counting UV Detector	BSMCPs + GaN Photocathodes AR+DD+EMCCDs	Major increase in QE for large format, low background, versatile detectors	5-10*
Next Generation UV Coatings	Atomic Layer Deposition	<ul style="list-style-type: none"> High reflectivity coatings → high performance instruments+telescopes Broad-band coatings → 100-120 nm coverage: key UV range Ultra-uniform coatings → Joint Exoplanet/UV astrophysics mission 	3‡
Next Generation Diffractive optics	Electron beam lithographic patterning	<ul style="list-style-type: none"> Arbitrary groove profile and shape High performance spectrographs High efficiency Low scatter Wide-field, multi-object, high efficiency spectrographs 	2-4§
Nano-materials for apolarization	nanofabricated optical surfaces?		?
Nanodetectors: UV/Visible discrimination	IR detectors Si multilevel detectors	Solar blind high QE UV detectors	?
Total Improvement Factor	Data grasp ($A_{eff} \times N_{objects}$) factor	20-250	
	Aperture reduction factor (linear): F_A	2-4	
	Cost reduction factor: F_A^2	4-16 (e.g., 10B\$ → 600M-2.5B\$)	

Notes: *Improvement from quantum efficiency enhancement over existing UV photon-counting detectors. Improvements in signal-to-noise ratio may exceed this factor because of lower dark noise. ‡Improvement in total reflectivity of a 3 reflection telescope and a 5 reflection wide-field, multi-object, high-resolution, aberration-corrected UV spectrograph. §Improvement in groove efficiency and total reflectivity for high-dispersion diffraction gratings (x2) and improvement in field-of-view of aberration-corrected wide-field UV spectrograph using arbitrarily curved grooves.

7.3 Study Evaluation

The KISS UV technology study was remarkably productive and rewarding. The study team was selected to represent a broad cross-section of the community. Technologists, mission implementers, and pure observers were brought together in many cases for the first time. Many of these groups have competed in the past and will in the future. The discussions were frank, informative, and sometimes contentious. This is exactly as we had hoped. New collaborations were formed, and many new ideas sprung forth from the lively discussions. Some of these concepts were immediately pursued by subgroups of the study participants as proposals or “quick-look” experiments in the laboratory.

The make up of the study participant, which included enthusiastic and inquisitive post-doctoral fellows and graduate students, made interactions very enjoyable and productive. Our study

greatly benefitted from having Professor Edoardo Charbon as a Distinguished Visiting Scientist (DVS). In addition to the two workshops and the interim study, he had a month-long visit and very fruitful interaction period at JPL's MicroDevices Laboratory (MDL) in particular with the Advanced UV/Visible/NIR Detector Arrays, Imaging Systems, and Nanosciences Group. Collaborations with Professor Charbon continue to expand. Our study also enjoyed co hosting a public lecture along with JPL's Office of Chief Technologist. The public lecture was given by Prof. Eric Fossum of Dartmouth College entitled, "Photons to Bits and Beyond: Science, Technology, and History of Digital Image Sensors." The talk was well attended

The study periods were deftly run by Michele Judd and the excellent KISS staff. Their patience, humor, and team-building contributions made the studies enjoyable and built team spirit.

7.4 Concluding remarks

We entered the study with optimism and some trepidation. We are living a time of countervailing forces, with great scientific excitement from a remarkable series of NASA science missions, juxtaposed with the threat of significant retrenchment in future science investments. The outstanding progress in new fabrication technologies, the power and breadth of UV measurement diagnostics, and the large margin for improvement in UV measurement capabilities makes this time ripe for new ideas and investments. This KISS study is perfectly timed to plant the seeds for novel technologies that will enable new, moderate scale, cutting edge missions over the next 10 years. It is very likely that one of the legacies of the KISS study will be the next major UV mission.

8 Acknowledgements

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9 Appendices

9.1 Appendix I: References

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9.2 Appendix II: List of Participants

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9.3 Appendix III: First Workshop Agenda

Short Course: Overview of Science, Technology Key Points, New Horizons

Paul Scowen (ASU)	UV Spectroscopy/Imaging and Science Questions (11 MB pdf) (video)
Michael Hoenk/Frank Greer (JPL)	What is on the Surface? (video) Atomically precise surface and interface engineering via atomic layer deposition to enable high-performance materials, detectors, and instruments (2.5MB pdf of Frank Greer's presentation)
Nai-Chang Yeh (Caltech) / Doug Bell (JPL)	Nanotechnology and its relevance to UV Science (video) (4.4 MB pdf of Doug Bell's presentation)
Kevin France, Chris Martin, Bruce Woodgate, Amanda Hendrix, Hakeem Olusheyi, Wes Traub	Panel Discussion on UV/Optical Science (video)

Overview: UV Science Questions in Astrophysics, Cosmology, Heliophysics, Protoplanets, Exoplanet Atmospheres, and Planetary Systems

Chris Martin	Welcome and Workshop Overview
Hakeem Olusheyi	Heliophysics Lightning Talk
Kevin France, University of Colorado	From Protoplanetary Disks to Exoplanetary Atmospheres (2.4 MB pdf)
Chris Martin, Caltech	Astrophysics/Cosmology Lightning Talk
Amanda Hendrix, JPL	Current Questions in UV Planetary Science (17.5 MB pdf)

Technology Overview: Optics, Gratings and Spectrometers, Dectors, New Materials

Matthew Beasley, CU-Boulder	Optical Systems for the UV (14.5 MB pdf)
Dan Wilson, JPL	Spectrometers/Gratings
David Schiminovich, Columbia University	History, Successes, Limitations, Future Projections
Oswald Siegmund, UC Berkeley	Advances in microchannel plates and photocathodes for photon counting detectors (2.7 MB pdf)
Bruce Woodgate, NASA GSFC	GaN Photocathodes and EBCMOS Detectors for UV Astronomy (9 MB pdf)
Patrick Morrissey, Caltech	Ultraviolet Detectors for Low Surface Brightness Astronomy (11.6 MB pdf)
Edoardo Charbon, Delft University of Technology	Single-Photon Imaging: Myth and Reality (129 MB pdf)
Shadi Shahedipour, State University of New York-Albany	Photon Detectors: Gallium Nitride Based Device Overview
Lis Nanver, Delft University of Technology	PureB silicon photodiode detectors for DUV/VUV/EUV light and low-energy electrons
Ben Mazin, UC Santa Barbara	Optical Lumped Element MKIDs

9.4 Appendix IV: Merged Breakout Groups and Members

Nanotechnology/Filters/Coatings	Detectors	UV/Optical/Exo/Planetary
Doug Bell (Chair, Nano)	Michael Hoenk (Chair)	Paul Scowen (Chair)
Matt Beasley (Chair, coatings/Filters)	Ben Mazin	Cynthia Froning
Cynthia Froning	Sam Cheng	Todd Veach
Matt Matuszewski	Todd Veach	Shouleh Nikzad
Greg Holsclaw	Mary Beth Kaiser	Chris Martin
Kris Bertness	Edoardo Charbon	Wes Traub (Chair, Exo)
Dan Wilson	Lis Nanver	Kevin France
Shadi Shahedipour	Tim Goodsall	Hakeem Oluseyi
Frank Greer	Paul Scowen	Amanda Hendrix
David Schiminovich	Alice Reinheimer	Todd Veach
Erika Hamden	Cynthia Froning	
Patrick Morrissey	Ossy Siegmund	
Ben Mazin	Bruce Woodgate	
Mary Beth Kaiser	Patrick Morrissey	
	Hakeem Oluseyi	
	Kevin France	
	Shadi Shahedipour	
	Kris Bertness	
	Shouleh Nikzad	

9.5 Appendix V: Professor Edoardo Charbon, DVS

My experience as 2011 W.M. Keck Institute for Space Studies (KISS) Distinguished Visiting Scholar was a positive one. I had a chance to participate in a small community of researchers in a small, informal setting that could enable a healthy exchange of ideas and experiences. The workshops were aimed at studying next generation UV instrument technologies enabling missions in the context of research on Cosmology and Planetary Sciences.

Working with KISS has been a very interesting and constructive venture. The experience as a KISS DVS was extremely rewarding both from the educational and human perspectives. I learned a lot in the study during the ex-cathedra presentations, brainstorming, and after-study social dinners and I hope to have been informative to my colleagues. The informal, yet intense atmosphere, as well as the infrastructure KISS gave us, has been facilitating a constant reflection upon the various problems our colleagues in Astronomy and Astrophysics face every day and how the sensor community can help.

Discussing new ground and space based instruments whose core is today's technology and preparing for next-generation instruments based on tomorrow's technology were the main goals of the study. Equally interesting was to understand today's trends in science and the dreams for tomorrow. But the information was also flowing in the other direction, allowing astronomers and astrophysicists to think differently, outside the box, when exposed to new sensing paradigms and new tools currently being developed in the sensor community.

In addition to the workshops, I spent a fruitful and productive month at JPL 's Microdevices Laboratory where I had close interactions with members of technical staff especially with the Advanced UV/Vis/NIR Detector Group. We have begun collaborations and will continue to work toward more interactions.

In summary, I believe that the DVS initiative is a very useful one, fostering the interaction of scientists around the globe in a collaborative and constructive fashion, enabling great advances in a common future of discoveries and technological advances.

9.6 Appendix VI: JPL-wide Seminar by Prof. Charbon.

In addition to this formal JPL-wide seminar (announcement below), Prof. Charbon delivered a series of informal seminars and held brainstorming sessions at JPL's MDL during his "mini sabbatical" at JPL.

Single-Photon Imaging: Myth and Reality

Professor Edoardo Charbon

TU Delft, Netherlands

Wednesday 24 August 2011, 2 pm JPL 180-101

Why do we want to detect photons? This is not a purely academic quest. Time-resolved single-photon detection has recently given way to time-resolved imaging with the emergence of deep-submicron CMOS SPADs, or single-photon avalanche diodes. SPADs enable to see inside quantum phenomena. Understanding how to model macroscopic phenomena using the quantum paradigm has enabled breakthroughs in a number of disciplines from computer vision to telecommunications, but it is in bio-detection and biomedical imaging that holds even a greater potential.

Thanks to large, massively parallel CMOS SPAD arrays, the design of scalable single-photon imagers has become a reality, but SPAD imagers are not for everyone. SPAD pixels exhibit high sensitivity and dynamic range, however it is high speed and low jitter that defines them, together with high stability and reproducibility. Due to the digital nature of SPADs, imaging architectures may be simplified, making complex readout schemes a thing of the past. Time-of-arrival detection can now be implemented on chip or even on-pixel while reconfigurable time-to-digital converters (TDCs) can also be used to exploit the torrid pace of growth in FPGA technology.

In this talk I will discuss device physics of SPADs, imager issues, and architectures, discussing performance and expectations. I will present recent developments and future research directions, focusing on bioimaging, often discussing ideas that will be essential in defining the next generation of single-photon imagers.



Edoardo Charbon (SM'00) received the Diploma from ETH Zurich in 1988, the M.S. degree from UCSD in 1991, and the Ph.D. degree from UC-Berkeley in 1995, all in Electrical Engineering and EECS. From 1995 to 2000, he was with Cadence Design Systems, where he was the architect of the company's initiative on information hiding for intellectual property protection purposes. In 2000, he joined Canesta Inc. as its Chief Architect, leading the development of wireless 3-D CMOS image sensors. Canesta was sold to Microsoft Corp. in 2010. Since November 2002, he has been a member of the Faculty of EPFL in Lausanne, Switzerland, working in the field of CMOS sensors, biophotonics, and ultra low-power wireless embedded systems. In Fall 2008 he has joined the Faculty of TU Delft, as full professor in VLSI design, succeeding Patrick Dewilde.

Dr. Charbon has consulted for numerous organizations, including Texas Instruments, Agilent, and the Carlyle Group. He has published over 200 articles in technical journals and conference proceedings and two books, and he holds 13 patents. His research interests include high-performance imaging, quantum integrated circuits, and design automation algorithms. Dr. Charbon has served as Guest Editor of the TRANSACTIONS ON COMPUTER-AIDED DESIGN OF INTEGRATED CIRCUITS and SYSTEMS and the JOURNAL OF SOLID STATE CIRCUITS and as Chair of technical committees in ESSCIRC, ICECS, ISLPED, and VLSI-SOC. Dr. Charbon is the KISS

Distinguished Visiting Scientist for the “Next Generation UV/Optical Instrument Technologies” study that is lead by Shouleh Nikzad, Prof. Chris Martin, and Prof David Schiminovich

9.7 Appendix VII: Public Lecture by Professor Eric Fossum



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The Keck Institute for Space Studies and
JPL Office of Chief Scientist and Chief Technologist
present a public lecture on

Photons to Bits and Beyond: The Science and Technology of Digital Image Sensors

Professor Eric Fossum
Dartmouth College

Dr. Eric R. Fossum is Professor of Engineering in Dartmouth's Thayer School of Engineering and a consultant to Samsung Electronics Semiconductor R&D Center. One of the world's leading solid-state image sensor device physicists, he has more than 135 US patents to his name. He is best known for inventing the CMOS image sensor. Today, his "camera-on-a-chip" technology is used in nearly all camera phones and webcams, digital-still cameras, high-speed motion capture cameras, automotive cameras, dental x-ray cameras, and swallowable pill cameras. This year he was inducted to the National Inventor's Hall of Fame.

Friday, November 11, 2011
5:00 - 6:00 pm
Hameetman Auditorium
Cahill Building
California Institute of Technology

Digital cameras are now small and everywhere, from cell phones to iPads to webcams to pill cameras to automobiles to digital SLRs to Mars Rovers. The images from these cameras shape our culture on a daily basis, from Facebook and Skype to unforgettable images of the Japanese tsunami and the Arab Spring. This presentation will address the science and engineering technology behind capturing these images, as well as a brief history of how this technology transferred from the lab at JPL into your cell phone. Future technology directions including the Quanta Image Sensor (QIS) will be discussed.

No registration is required.
Seating is limited and is available on a first come, first served basis.
This lecture will be videotaped.

9.8 Appendix VIII: Narratives on some of the promising technologies

Cryogenic Detectors

Ben Mazin (UC Santa Barbara)

Cryogenic detectors are currently the preferred technology for astronomical observations over most of the electromagnetic spectrum, notably in the far infrared through millimeter (0.1– 3 mm), X-ray, and gamma-ray wavelengths ranges. In the important ultraviolet, optical, and near infrared (0.1–5 μm) wavelength range a variety of detector technologies based on semiconductors, backed by large investment from both consumer and military customers, has resulted in detectors for astronomy with large formats, high quantum efficiency, and low readout noise. However, these detectors are fundamentally limited by the band gap of the semiconductor (1.1 eV for silicon) and thermal noise sources from their high (~100 K) operating temperatures. Cryogenic detectors, with operating temperatures on the order of 100 mK, allow the use of superconductors with gap parameters over 1000 times lower than semiconductors. This difference allows a leap in capabilities. A superconducting detector can count single photons with no false counts while determining the energy (to several percent or better) and arrival time (to a microsecond) of the photon. It can also have much broader wavelength coverage since the photon energy is always much greater than the gap energy. While a CCD is limited to about 0.3–1 μm , the MKIDs described below can photon count from 0.1 μm in the UV to greater than 5 μm in the mid-IR, and are capable of being used as bolometers out through the millimeter, enabling observations at infrared wavelengths vital to understanding the high redshift universe.

This approach has been pursued in the past with two technologies, Superconducting Tunnel Junctions (STJs) and Transition Edge Sensors (TESs). While both of these technologies produced functional detectors, they are limited to single pixels or small arrays due to the lack of a credible strategy for wiring and multiplexing large numbers of detectors, although recently there have been proposals for larger TES multiplexers.

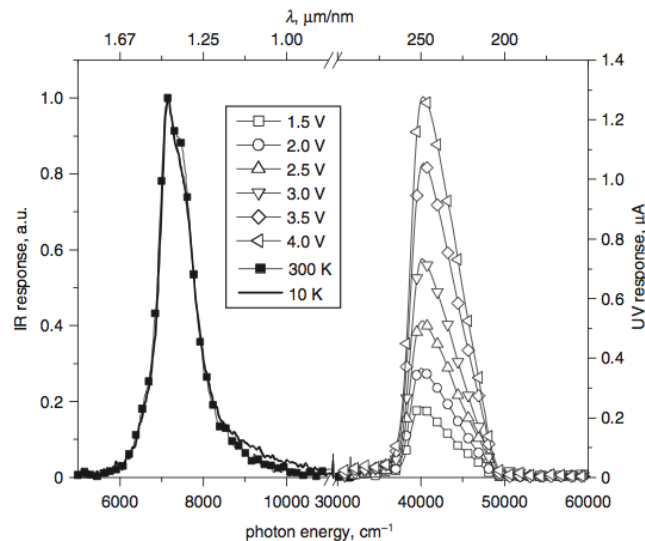
Microwave Kinetic Inductance Detectors, or MKIDs, are an alternative cryogenic detector technology that has proven important for millimeter wave astrophysics due to their sensitivity and the ease with which they can be multiplexed into large arrays. MKIDs use frequency domain multiplexing that allows thousands of pixels to be read out over a single microwave cable.

These arrays will have significant advantages over semiconductor detectors. They can count individual photons with no false counts, and determine the energy (to several percent) and arrival time (to a microsecond) of every photon with good quantum efficiency, over 80% in the UV. Since MKIDs determine the energy of every incoming photon, they can bypass requirements for solar blindness as long as the count rates do not exceed around 2000 cts/pixel/second.

While current arrays are 32x32 pixels, MKIDs scale well and with continued investment could reach Megapixel array sizes within a decade. MKIDs have the highest potential of any UV detector technology except for the widest field of view applications.

Proposal for a Quantum Cascade Detector for Compact UV Single-Photon Image Sensing by Edoardo Charbon, TU Delft

Quantum cascade detectors (QCDs) are an emerging technology that is showing promise in single-photon detection at a large range of wavelengths from UV, visible, to NIR. The main advantages of this technology are selectivity, compactness, and GaN compatibility. The figure below shows a typical response observed in a QCD detector as a function of wavelength [1].



The structure of the QCD we propose to implement is based on a series of thin films of AlGa_N and/or a AlN/GaN superlattice to achieve, for example, a dual band detection. A feedback amplifier (either external or integrated) with programmable gain and bandwidth should be added in this setup to ensure the proper functionality. These films can be grown by plasma-assisted molecular-beam epitaxy on a commercial AlN-on-sapphire or other appropriate substrates. Responsivities of 10mA/W are expected in a 250nm to 350nm wavelength range.

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APD / CMOS hybrid

Edoardo Charbon (TU Delft)

In a hybrid approach different technologies, processed independently, can be combined into one chip. Many ways of doing this are being explored for a multitude of electronic, photonic and optoelectronic applications. Specifically for APDs the aim has been to increase the fill-factor and responsivity for megapixel imagers. Originally reported technologies for achieving this include joining foundry chips by bump bonding or epoxy bonding the APDs to foundry chips, which delivered coarse (100 μ m) pixel spacing and 0.5 ns timing quantization [1]. More recently Lincoln Laboratory has demonstrated a fully depleted SOI CMOS fabrication process and techniques to fabricate three-dimensional integrated circuits by stacking SOI wafers to form multiple “tiers” of circuitry interconnected with micron-scale vias [2]. Such a 3D integration process could enable new computing architectures that exploit short, massively parallel interconnections between tiers. They presented a 3D-integrated 3-tier 64 \times 64 lidar focal plane with 50 μ m pixel spacing and circuitry added to the pixel to refine the timing quantization. Timing quantizations of 130ps and 110ps are obtained, respectively, for the rising and falling clock edges. Power distribution issues and a readout clock race condition constrained operation to a timing resolution of 2ns.

1. Comparison with State-of-the-Art

The main improvement is in fill-factor which can be brought from something like 25% close to 100%. Responsivity can be improved by a better APD design due to an alleviation of the restrictions set by the other electronic functions and by combining tiers dedicated to different detector technologies.

2. Advantages / Impact (provide context *vis a vis* mission/instrument applications)

Versatility: Because of the hybrid nature, the detector and readout can be optimized independently. Furthermore, the readout can be use with different detector arrays (e.g., silicon, InGaAs, HgCdTe) thereby allowing the system simplicity for an instrument with a wide spectral range.

3. Areas to improve / develop (advance TRL)

In this case it is a question of trying out the available technology for our application. There is an enormous research/development effort going on in the area of 3D integration from which the specific integration of UV detectors can profit. Experience with the design issues need to be developed for an optimal application of the available possibilities.

4. Cost / time.

One tape-out each year or half year. Price depends on foundry.

Quantum Image Sensors

Edoardo Charbon, TU Delft

5. Technology description

The fundamental idea is to partition pixels onto mini-pixels smaller than the minimum Abbe's dimension. Each pixel is digital (ideally) single-photon sensitive. Gray levels are extracted from the density of 1's and 0's. The entire array is used to reconstruct the gray level of each pixel by proper weighting functions.

6. Comparison with State-of-the-Art

The idea was originally suggested in the 1970s upon the invention of the digital memory. Exploitation of this idea to its full potential was not possible until deep-submicron processes have become available for image sensors.

7. Advantages / Impact (provide context *vis-à-vis* mission/instrument applications)

The technology is versatile; it enables optically matched sensors with highly uniform, logarithmic response and theoretically infinite dynamic range. Software imaging or computational image sensors will be enabled by this technology. In space it will allow highly redundant pixels and thus high resilience to localized sensor and optics damage thanks to the capability of self-reconfigurability to maximize image quality and to keep hot spots under control.

8. Areas to improve / develop (advance TRL)

To the best of my knowledge only one such sensor has been built (Yoon and Charbon, IISW 2011). A QIS would require great computational capacity (possibly) built *in situ* and thus high transistor density.

9. Cost / time.

It will take significant effort to achieve QIS implementations. Concrete results are expected in the medium term.

Single Photon Avalanche Diode (SPAD)

Edoardo Charbon, TU Delft

1. Technology description

An optical or UV SPAD is a reverse-biased pn junction operating in Geiger mode, so as to detect single photons; it is also known as Geiger-mode avalanche photodiode (GAPD). A CMOS SPAD is a SPAD implemented in a CMOS process; it can operate in frontside illumination (FSI) and backside illumination (BSI) regimes; in the latter regime a substrate thinning and surface processing techniques, such as PureB or delta-doping, are required for UV detection. Upon detection of a photon, SPADs generate a digital signal that is fully CMOS compatible; it can be used by further digital processing on- or off-chip.

2. Comparison with State-of-the-Art

CMOS SPADs have been fabricated for visible and IR detection using silicon and Ge-on-Si implementations (Sammak et al., IEDM2011). UV CMOS SPADs don't exist except for NUV applications. In this case they are implemented in silicon.

3. Advantages / Impact (provide context *vis-à-vis* mission/instrument applications)

SPAD arrays are generally low-cost, low-power, and compact in nature. They have also been demonstrated to be radiation hard (Carrara et al., ISSCC2009). For this reason, they may become suitable to be included in planetary missions whereby higher dark count rates may be acceptable but time resolution is critical. Typically timing resolutions of 100ps per pixel on large arrays of pixels are routinely achieved on CMOS substrates (Niclass et al., JSSC 2008, Veerappan et al., ISSCC2011, etc.).

4. Areas to improve / develop (advance TRL)

UV SPADs implemented with PureB on a pn silicon junction (Sakic et al., IEDM2010) and delta-doping implemented on a SOI back-thinned chip could significantly improve QE in NUV while potentially improving the noise performance. Dark counts may be further improved by reducing tunneling by way of appropriately doping the multiplication regions and improving the guard rings used in SPADs for premature edge breakdown mitigation.

5. Cost / time.

It will take a moderate investment to transfer the current PureB and delta-doping techniques to back-thinned implementations of SPADs in SOI.

AlGaN Avalanche Photodetector (array)

Shadi Shahedipour (SUNY-Albany, CNSE)

The III-nitrides are physically and chemically robust, can be doped both n and p type, and have been shown to achieve high QE as photo-detectors, detector arrays, and photocathodes. These are among the attributes that make III-nitride materials nearly ideal for detectors with gain, i.e., APD designs. This technology reduces the size, mass, power, and cost of future ultraviolet (UV) detection instruments by using lightweight, low-voltage AlGaN detectors in a hybrid detector/multiplexer configuration. The solar-blind feature eliminates the need for additional visible light rejection and reduces the sensitivity of the system to stray light that can contaminate observations. The device is most sensitive to UV radiation when operated in the photovoltaic mode at or near zero-reverse bias voltage.

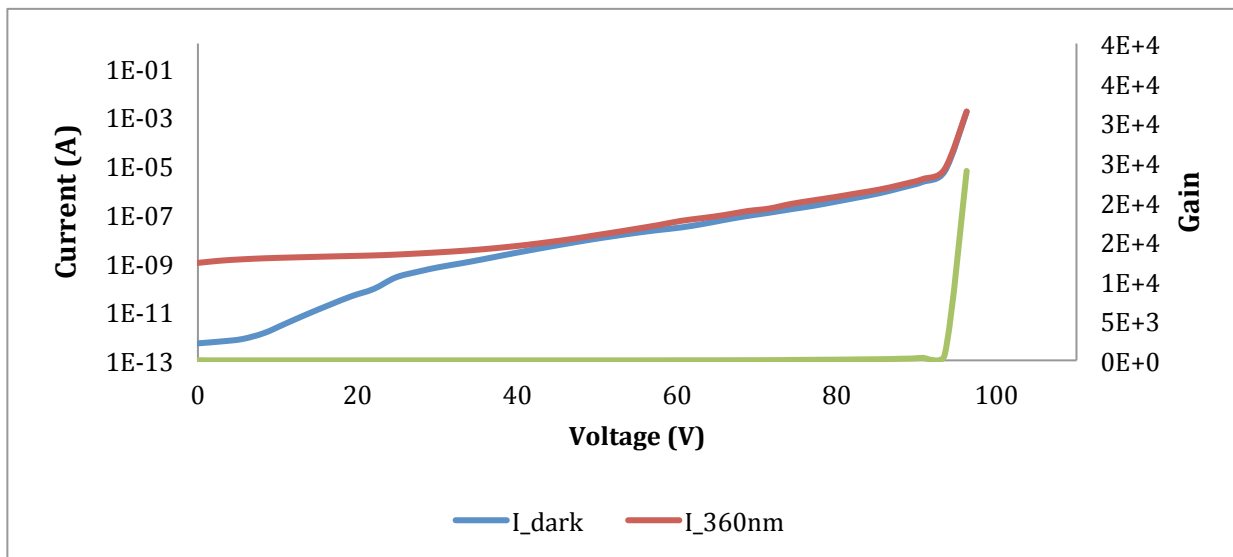
The AlGaN UV detector operating at 325 nm gives a 1,000× better extraterrestrial solar radiation rejection than silicon. This reduced need for blocking filters increases the quantum efficiency (QE) and simplifies the optical systems. The wide direct bandgap reduces the thermally generated dark current to levels that allow many observations at room temperature. Because of this, the AlGaN UV photodiode array doesn't require the extensive cooling (and the associated cooling cost, complexity, and weight) that silicon does, significantly reducing system cost. Wide direct bandgap materials are naturally more radiation tolerant, which is crucial for instruments located outside of Earth's atmosphere.

Detectors based on AlGaN have shown great potential for UV detection due to their direct wide bandgap. However, several materials challenges have stood in the way of producing high quality AlGaN APD structures that can be integrated with Si CMOS readouts. The key issue in large part is the high density of dislocation defects due to the large lattice mismatch between the III-nitride layer and the commonly used substrates (e.g. Sapphire, SiC, Si).

Solar blind Schottky, p-i-n, and simple Metal Semiconductor Metal (MSM) photodetectors with excellent detectivities have been reported in the last several years. Only a few GaN-based APDs have been reported in the literature. Geiger-mode operation has been demonstrated in GaN with a peak response at 362 nm corresponding to the GaN bandgap and linear-mode operation has been demonstrated in $\text{Al}_{0.38}\text{Ga}_{0.62}\text{N}$ with a peak response at 278 nm. These initial demonstrations are very promising, and indicate that with improvements in the material quality and device design GaN-based APD arrays are within reach. However, several problems must be addressed to achieve this goal. For example, yields were very low in the GaN APD devices due to defect-related micro-plasmas in the material. Yields have not yet been reported for AlGaN-based devices. As argued by the authors, larger devices show very high dark current which is direct evidence of the effect of defects in the material rather than processing-related defects. As was shown previously in GaN-based APDs and now in AlGaN Solar-blind APDs, material quality is

the major issue in achieving high efficiency APDs. GaN based APD structure on bulk GaN substrate with defect density in the 10^7 cm^{-2} is demonstrated to have three order of magnitude lower dark current as compared to similar structure on lattice mismatched sapphire substrate. *We (UAlbany-CNSE/JPL team) have recently demonstrated avalanche action in GaN pin device structure with a gain of 80K at a bias of 85V for a 40 μm device.* This was mainly achieved by passivation of surface states. It is expected that improvement in p-layer conductivity, higher quality material (lower defect density), along with novel device structure design (SAM design, confined multiplication region, and backillumination) will result in >one order of magnitude in dark current directly translating into higher quantum efficiency, and higher gain at lower voltages.

Multiple groups have demonstrated focal plane imager based on AlGaIn p-i-n photodiodes. In array format, a rejection ratio of greater than three order of magnitude (10^3) is observed before and after the cutoff edge (365nm for GaN pin). In one report for a large format array, the QE is seen to fall rapidly with decreasing wavelength reaching a minimum of 3 percent at 345 nm. [Shahid Aslam and David Franz of Goddard Space Flight Center, 2010] The detector's current responsivity at 360 nm and 0 V bias is 0.13 A/W. The spectral detectivity is $2.6 \times 10^{15} \text{ cm Hz}^{1/2}\text{W}^{-1}$, corresponding to a detector noise equivalent power of $4.1 \times 10^{-18} \text{ W/Hz}^{1/2}$.



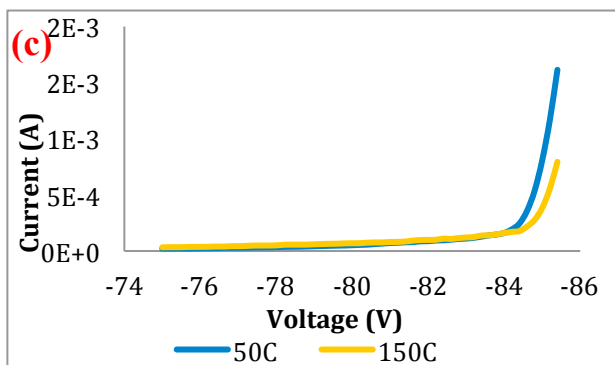
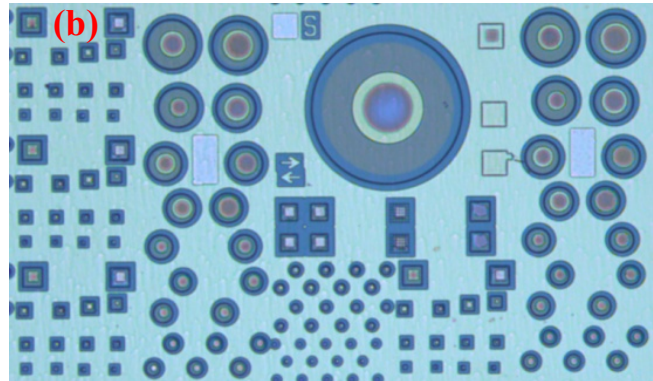
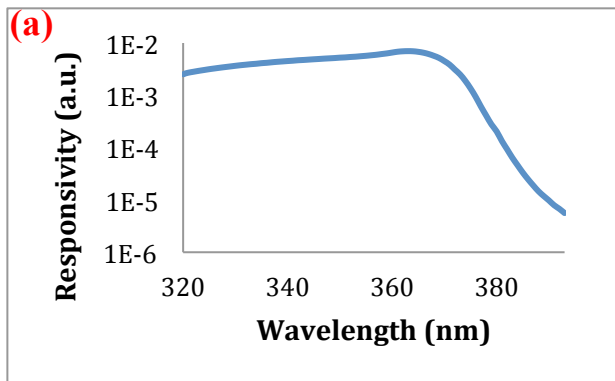


Figure 2: **a)** Spectral response of the GaN APD shows a 3 order of magnitude rejection ratio between UV/VIS. **b)** Optical image of the fabricated APDs with devices of different dimensions. **c)** Temperature dependent IV of a reversed bias APD showing the positive temperature coefficient of the breakdown voltage, confirming the nature of the breakdown to be avalanche multiplication.

Borosilicate MCP Summary

Ossy Siegmund, UC Berkeley

MCP electron imaging amplifiers were introduced in the early 1960s as an outgrowth of work on single channel continuous dynode multipliers, and have since become a mainstay of many classes of imaging system. Initially used as an element in image intensifiers, the MCPs direct sensitivity to electrons, ions, and x-rays have resulted in an enormous range of applications, from UV astronomy to electron spectroscopy. Wiza [1979], gives a good insight into the operation and range of applications of these devices [Eberhart 1979, Fraser 1983, Matsuura [1984], Siegmund [1985, 1988, 1989]]. The pore sizes used today range from 2 to 25 microns, with 6 to 10 microns a more typical range in astronomy. The channel length to pore size ratio is typically in the range 40 – 120:1 and sizes of ~100 mm diameter are available. Single plates have an electron gain typically in the range 10^3 - 10^4 . In order to achieve higher gains, MCPs are often used in a stacked configuration of two ("chevron") or three ("Z stack") parallel plates in close proximity, with opposing bias angles. Gains of $>10^7$ are then readily achieved. In addition to these useful characteristics, MCPs also have:- the capability to match a focal surface using a curved MCP [Martin 2003, Bloch 1994], room temperature operation, radiation hardness and bandpass selectivity (e.g. solar blindness Tremsin 2000b)).

Many electronic imaging array detectors use MCPs as a photoelectron amplifier in front of a two dimensional patterned anode such as a cross delayline [Siegmund 1999a], cross strip [Siegmund 2001a, Siegmund 2003a, Tremsin 2004a, Tremsin 2006a], silicon CCD or CMOS (medipix, timepix) [Vallerga 2008a, 2008b, Bellazzini 2008, Vallerga 1997]. Each readout technique is optimized for the particular imaging science required (e.g. high spatial and temporal resolution, very high rate, low gain, high dynamic range etc.). Over the last twenty five years, these readouts have improved their spatial resolution by a factor of 10, their count rates by a factor of 1000, and the corresponding gain required to achieve high resolution has decreased by a factor of ~100. MCP detectors can now reach spatial resolutions of $<10\mu\text{m}$ FWHM [Siegmund 2001a, 2003a, Tremsin 2004a, Vallerga 2008a], photon counting rates of many MHz [Vallerga 2008a, 2008b], and lifetimes of 10^{10} events/ mm^2 [Martin 2003]. Over the same period, parameters strictly limited by the MCP itself, such as area, pore size, gain, and lifetime (as measured in Coulombs/ mm^2) have, only improved by a factors of ~ 2, and are a major cost element for large ($>7 \times 7\text{cm}$) areas.

A potentially substantial improvement in MCP performance, scope and robustness for astronomical applications using the technique of atomic layer deposition (ALD) onto borosilicate glass substrates to make a new generation of microchannel plates. The MCPs are based on a novel concept where the substrate is constructed from a borosilicate (700°C softening point) micro- capillary array that is made to function as an MCP by deposition of resistive and secondary emissive layers using atomic layer deposition (ALD) [Leskelä 2003, Mane 2011]. This differs from conventional MCP lead glass construction [Lampton 1981], removing the need for chemical etching and H_2 reduction steps, allowing the operational parameters to be set by tailoring the sequential ALD deposition processes. The process is relatively inexpensive

compared with conventional MCPs and allows very large MCPs to be produced with pore sizes in the 40 μm to 10 μm range, and open areas up to 85% rather than $\sim 60\%$ for conventional MCPs. Initial work has already been done [Siegmond 2011] with smaller test MCPs which shows they provide many performance characteristics typical of conventional MCPs, and they have now been made in sizes up to 20 cm, have low intrinsic background ($0.085 \text{ events cm}^{-2} \text{ s}^{-1}$) and very stable gain behavior for at least 2.5 C cm^{-2} of charge extraction.

The photon sensitivity (QE) of MCP detectors is determined by the photocathode choice and the detection of the photoelectron by the MCP [Siegmond 1998] for further amplification. Opaque photocathodes, which we usually directly deposit on the MCP [Siegmond 1990, Jelinsky 1996, Tremsin 2001a, Larruquert 2002, Tremsin 2003, Tremsin 2005a] tend to have a higher QE than proximity focused semitransparent mode cathodes deposited on a window directly in front of the MCP. However, current MCP technologies are not compatible with direct deposition of some potentially new high performance photocathodes (GaN) on their surfaces, both chemically and thermally, as the deposition temperatures can be too high for the current MCP glass or the composition incompatible. Though the QE is largely determined by the interplay of the absorption coefficient of the photocathode and the photoelectron escape length, the probability of detecting the first photoelectron by the MCP is also very important [Siegmond 2005]. The open area ratio of the pores and the secondary electron emission coefficient vs. input electron energy both affect the detection quantum efficiency of the detector as a whole. Typical opaque cathodes for $<200\text{nm}$ are alkali halides with up to 65% QE ($<115\text{nm}$), and up to 50% ($>115\text{nm}$) with cutoffs $\sim 190\text{nm}$. Opaque and semitransparent cathodes used for 200nm to 300nm have $<15\%$ QE, while semitransparent cathodes for 300nm – 900nm have peak efficiencies of $\sim 25\%$.

The ALD borosilicate MCPs offer a potentially cleaner, more robust (700°C softening point) and tolerant substrate for opaque photocathode materials. We have begun investigating this opportunity by depositing opaque GaN (p-doped, Cs activated) photocathode onto an ALD borosilicate MCP (NiCr surface) by molecular beam epitaxy. The value of QE values achieved are about half the QE obtained for opaque GaN photocathodes epitaxially grown on sapphire (Al_2O_3) substrates that we have measured previously [Siegmond 2008]. The latter give QEs as high as 80% at wavelengths of 120nm and a cutoff at $\sim 360\text{nm}$. However, it is significant that a high level of efficiency has been achieved on a non-optimal substrate and without a Cs deposition optimization process. Immediate improvements are potentially possible by optimizing the GaN deposition process, including the provision of an Al_2O_3 layer deposited onto the MCP by ALD [Mane 2011].

The possibility of using this type of ALD borosilicate MCP/photocathode to satisfy potential future applications for NASA Astrophysics has many advantages. Provided that MCPs with small pores (10 μm) can be developed, and functionalized with ALD, this technique could provide very large (20 x 20cm) area MCPs with high spatial resolution ($<20\mu\text{m}$), low in-orbit background rates ($<0.05 \text{ events cm}^{-2} \text{ sec}^{-1}$), better robustness (gain stable to $>10^{12} \text{ events/mm}^2$) and compatibility with new photocathode technologies (GaN, etc), and at a fraction of the cost ($\div 10$) of conventional MCPs. Other potential fields impacted by this work include homeland security applications (large area radiation monitoring), biology (fluorescence imaging/timing),

mass spectroscopy, high energy physics (Cherenkov imaging/timing), and materials research (high time resolution imaging photoelectron spectroscopy).

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Cs free GaN photocathode

GaN and AlGaN based photocathodes have attracted considerable attention for their application in image intensifiers, astronomy and UV detection and emission systems. Small electron affinity of AlGaN alloy allows development of high quantum efficiency negative electron affinity (NEA) photocathodes with significant advantages such as solar blindness, radiation hardness and low noise. Conventional photocathodes achieve NEA by cesiating the photocathode surface. Fabrication, optimization, and installation in vacuum is required for cesiated photocathodes due to the high chemical activity of the Cesium. Such requirement increases cost and limits the range of potential applications. Further, such photocathodes have been reported to suffer from chemical instability and degradation with time. *Recent reports made by the UAlbany-CNSE/JPL group have shown the potential of a novel Cs-free GaN based photocathode that utilizes band engineering near the photocathode surface to achieve permanent NEA.* Device structure is composed of a Mg doped GaN grown on sapphire substrate, followed by Si-delta doping and a thin n^+ GaN cap. By placing a Si delta doped layer on the Mg doped GaN surface conduction band of the overall structure is pulled close to the Fermi level of the p-GaN. A thin n^+ GaN cap is deposited to provide stability to the Si-delta doped layer. Device design parameters including Si-delta doping and thickness of n^+ GaN cap layers play a critical role in determining the emission threshold and quantum efficiency of the device. Further, polarization induced charges at the device surface influence the device characteristics. We have performed physics based simulations to optimize the device design parameters taking into account polarization induced surface charges. Device structures have then been epitaxially grown using a Veeco D180 MOCVD system and characterized using secondary ion mass spectroscopy (SIMS) and photoemission (PE) measurements. A series of growth experiments with varying conditions have been performed to optimize Si incorporation in the delta doped layer and quality and thickness of the n^+ GaN cap layer. Emission threshold of the device has been observed to increase with increase in the n^+ GaN cap thickness. Such behavior has been successfully modeled and is attributed to local electric fields caused by the negative polarization induced surface charges. Quantum efficiency of the device follows systematic exponential decay with increase in n^+ GaN cap thickness. Increase in Si incorporation in the delta doped layer, up to the optimum value, has shown to improve device characteristics. Further increase in Si incorporation caused increase in emission threshold and degradation of the photocathode surface.

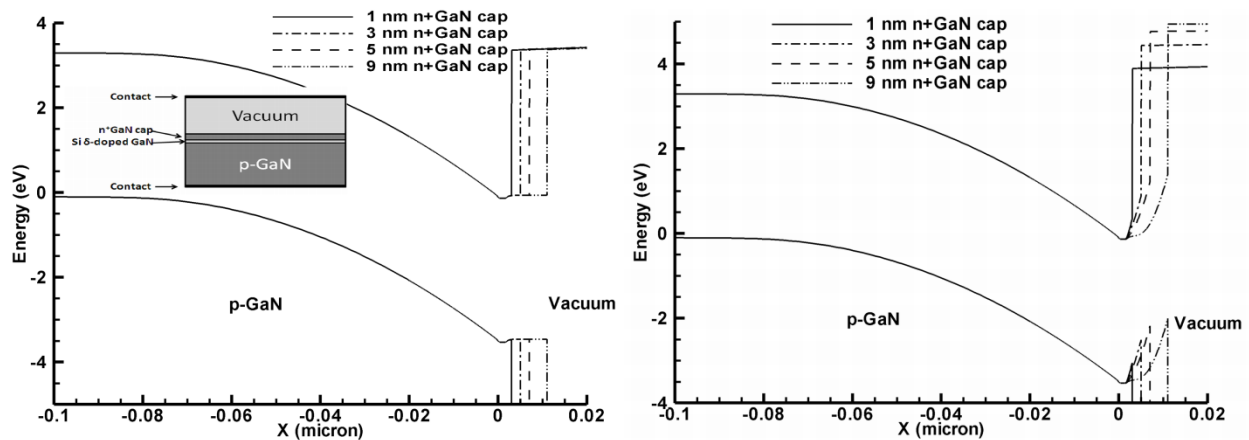


Figure 1: Simulated energy band diagram of photocathode devices without polarization (left) and with polarization (right). Inset in the left image shows the device design used in the simulation

Figure 2: Si depth profile as measured by SIMS for different silane flow and delta doped layer growth time. Silane flow for the n+GaN cap was kept same as the Si flow in delta doped layer

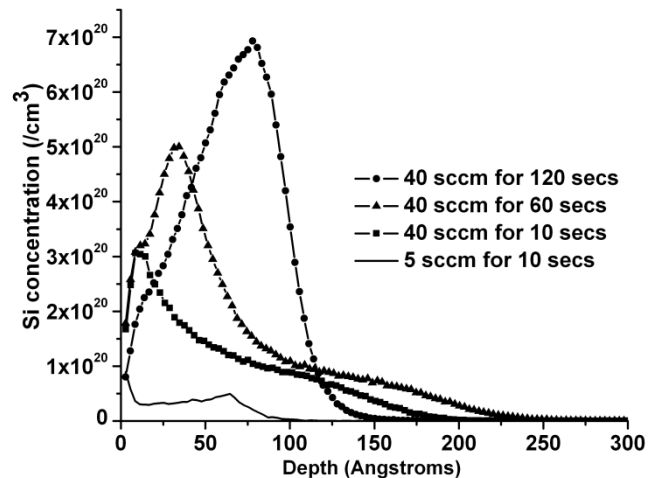


Figure 4: Quantum efficiency as a function of photon energy for different n+GaN cap thicknesses. Inset shows calculated emission threshold from the emission spectrum as a function of cap thickness

