# Development of Ultra High Sensitivity UV Silicon Carbide Detectors

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High sensitivity is always a goal for detectors in order to maximize the detection capability. The leakage current is one of the dominating factors limiting the sensitivity of a detector. The larger the bandgap energy, the lower the expected dark current. 4H-SiC has a bandgap three times larger (3.2eV) than Si and, thus, SiC detectors should have much higher sensitivity than Si detectors. A variety of 4H-SiC UV detectors with high sensitivity have been developed to improve the detector sensitivity in UV. In this paper, we will present the results of the 4H-SiC Schottky photodiode, p-i-n photodiodes, avalanche photodiodes (APDs), and single photon-counting avalanche diodes (SPADs). One of the key sensitivity parameters of photodetectors is the specific detectivity, $D^*$, which is an area-independent figure of merit. The greater the $D^*$, the higher the detector sensitivity. At zero bias where Johnson noise dominates, $D^*$ is expressed as[1]

$$D^*(\lambda) = \frac{q\eta}{h\nu} \cdot \left[ \frac{R_o A}{4k_B T} \right]^{1/2},$$

where $A$ is the detector area, $B$ is the bandwidth, $\eta$ is the quantum efficiency, $h$ is Planck's constant, $\nu$ is the radiation frequency, $k_B$ is the Boltzman constant, $T$ is the temperature, and $R_o$ equals to $(dV/dI)_{V=0}$ with $R_oA$ being area independent. Note that $D^*$ increases as $R_oA$ increases so $R_oA$ is also frequently used as a figure of merit for Johnson noise limited detectors.

4H-SiC Schottky photodiodes and p-i-n photodiode have been fabricated and tested in photovoltaic mode. On 1cm×1cm SiC Schottky photodiodes with semi-transparent Pt contacts, the leakage current at 0V is less than 1fA and the $R_oA$ product is $2.5\times10^{13}\Omega\text{cm}^2$. The maximum quantum efficiency is 37% and the corresponding $D^*$ is $3.6\times10^{15}$ cmHz$^{1/2}$/W. On p-i-n photodiodes, the leakage current can be further reduced. The leakage current for 1.5mm×1.5mm photodiodes at –100V is typically 100fA and the leakage current at 0V is below the detection limit. By extrapolating the leakage current at high biases, $R_o$ is estimated to be around $5\times10^{16}\Omega$ and the $R_oA$ product is $1\times10^{15}\Omega\text{cm}^2$. The maximum quantum efficiency is 78% and the corresponding $D^*$ is $4\times10^{16}$ cmHz$^{1/2}$/W. Figure 1 compares the $D^*$ of SiC Schottky and p-i-n photodiodes with other common photo detectors[2]. A dash line is used for p-i-n photodiodes because the dynamic resistance was calculated based on extrapolated results. As shown in the figure, the $D^*$ of SiC Schottky photodiodes is two orders of magnitude greater than the $D^*$ of Si photodiodes, and three orders of magnitude greater than the $D^*$ of Si CCDs. The $D^*$ of SiC p-i-n photodiodes is even higher and about one order of magnitude higher than the $D^*$ of SiC Schottky photodiodes. Note that the $D^*$ of SiC p-i-n photodiodes is of same order of magnitude as frequently used S20 PMT. Large area GaN Schottky photodiodes have also been fabricated for comparison and the results are included in Fig.1. The $D^*$ of the SiC Schottky photodiodes is two orders of magnitude greater than that of the GaN photodiodes and SiC p-i-n photodiodes is more than three orders of magnitude greater .

To achieve the maximum sensitivity, the noise from the readout electronics has to be eliminated. Usually, the bandwidth is reduced to minimize the noise contribution from the readout electronics but the speed is also reduced. APDs are the best way for semiconductor detectors to approach the ultimate sensitivity without compromising the speed.

4H-SiC APDs have been developed with a linear mode gain of $10^6$ in contrast to $10^3$ of Si APDs at the same order of magnitude leakage current density. By operating SiC APDs at a linear gain over $10^6$, single photon-counting APD (SPAD) has been demonstrated. Figure 2 shows the photon-counting spectra of a 160μm×160μm SPAD measured in the dark and under UV illumination. The sharp pulses correspond to electrons generated by *g-r* recombination in the dark and by photons under UV illumination. The counting probability of an absorbed photon is 75% and the dark count rate is ~600KHz. The $D^*$ of the demonstrated SiC SPADs has been calculated and plotted in Figure 1. Due to the very high electric field, the dark current of SPADs is significantly higher than that of SiC photodiodes and the $D^*$ is $\sim 10^{13}$ $\mathrm{cmHz^{1/2}/W}$. The $D^*$ is expected to be significantly increased as the improvement of the SiC crystal quality continues.

In summary, 4H-SiC Schottky and p-i-n photodiodes, APDs, and SPADs have been fabricated to study the sensitivity of SiC detectors. Due to the availability of high quality wide bandgap SiC and the development of processing technology, 4H-SiC detectors offer unprecedented $D^*$ in UV. The maximum $D^*$ of $3.5\times10^{15}$ $\mathrm{cmHz^{1/2}/W}$ and $4\times10^{16}$ $\mathrm{cmHz^{1/2}/W}$ has been achieved on Schottky and estimated on p-i-n photodiodes. SiC SPADs have also been demonstrated for the first time which could be further improved to provide the ultimate sensitivity.

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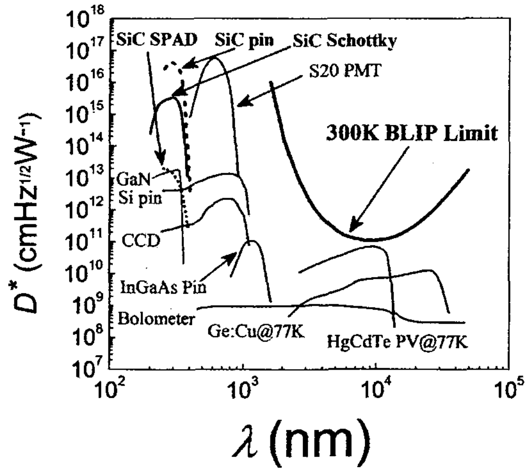

Figure 1 Comparison of SiC photodiodes fabricated in this work with some common detectors. The 300K blackbody radiation limited $D^*$, 300K BLIP limit, is also included as a reference.

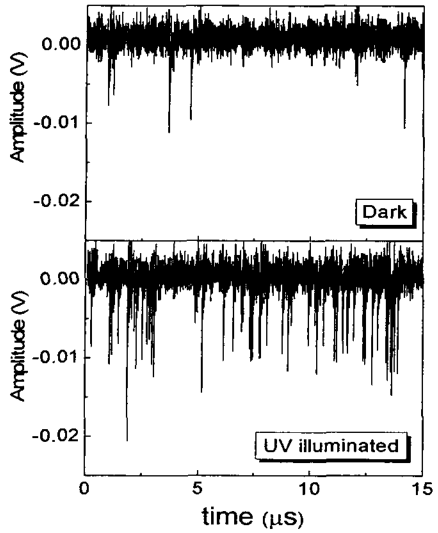

Figure 2 Photon-counting spectra of a 4H-SiC APD in dark and under UV illumination.

# Development of Ultrahigh Sensitivity Ultraviolet Silicon Carbide Detectors

***Abstract***: A variety of silicon carbide (SiC) detectors have been developed to study the sensitivity of SiC ultraviolet (UV) detectors, including Schottky photodiodes, p-i-n photodiodes, avalanche photodiodes (APDs), and single photon-counting APDs. Due to the very wide bandgap and thus extremely low leakage current, SiC photo-detectors showed excellent sensitivity. The specific detectivity, $D^*$, of SiC photodiodes are orders of magnitude higher than that of their competitors, such as Si photodiodes, and comparable to the $D^*$ of photomultiplier tubes (PMTs). To pursue the ultimate detection sensitivity, SiC APDs and single photon-counting avalanche diodes (SPADs) have also been fabricated. By operating the SiC APDs at a linear mode gain over $10^6$, SPADs in UV have been demonstrated. SiC UV detectors have great potential for use in solar blind UV detection and biosensing. Moreover, SiC detectors have excellent radiation hardness and high temperature tolerance which makes them ideal for extreme environment applications such as in space or on the surface of the Moon or Mars.