SOLAR ENERGY CONVERSION USING SURFACE PLASMONS FOR BROADBAND ENERGY TRANSPORT

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SUMMARY

This paper introduces a new strategy for efficient solar energy conversion based on parallel-processing with surface plasmons. The approach is unique in identifying: (1) a broadband carrier with suitable range for energy transport, and (2) a technique to extract more energy from the more energetic photons, without sequential losses or unique materials for each frequency band. The aim is to overcome the fundamental losses associated with the broad solar spectrum and to achieve a higher level of spectrum splitting than has been possible in semiconductor systems.

INTRODUCTION

In conventional silicon solar cells, 56 percent of the incident power is wasted because monoenergetic conduction electrons are used to transport a broad solar energy spectrum. In cascade and spectrophotovoltaic systems, spectral mismatch losses are reduced by using different semiconductors to support different energy carriers. However, the increased complexity and sequential losses offset incremental efficiency gains when more than two or three frequency channels are used.

A preferred route is to parallel process different carriers in the same material. The missing ingredient has been the identification of a broadband carrier with suitable range for energy transport. In the search for long-lived excited states, little attention has been paid to less stable, but relativistic waves, like the surface plasmon. Perhaps these collective modes were overlooked because their properties are unfamiliar, or more likely, they were ruled out due to a prevalent misconception that wave approaches are unsuited for incoherent light.

SURFACE PLASMONS

Surface plasmons (refs. 1 to 4) are guided electromagnetic waves, which can be supported on thin films of common metals, like aluminum or silver. Thicker substrates may also be used, and there may be native oxides or dielectric overlayers. However, an interface can not support surface plasmons unless the dielectric function has opposite sign in the two materials. Negative dielectric functions occur in the Restrahlen band or high reflectivity region of most metals and semiconductors.

The surface plasma wave (fig. 1) consists of a propagating wave of surface charge (polarized valence electrons) accompanied by transverse and longitudinal electromagnetic fields, which decay exponentially with distance from the metal interface. Typically, the fields extend a tenth to several thousand micrometers

above the metal, but only penetrate a few hundred angstroms into the substrate, permitting integration with back surface diodes. This also allows an extremely lightweight system for space use or a materials-conservative device on a low-cost substrate for terrestrial applications.

The surface plasmon spectrum is broad and continuous from the infrared to cut-offs which lie in the visible or ultraviolet depending on the material. The velocities are relativistic except near cut-off. For broadband energy transport, we are primarily interested in the relativistic waves, rather than the better known quasistatic ones, which are nearly monoenergetic.

Surface plasmons have finite range due to substrate absorption mechanisms like collision-broadening and interband transitions, as well as radiative loss induced by surface roughness. Landau-damping, or electron acceleration, can also be important but not for the relativistic waves. On an open surface the relativistic plasmons have field patterns in which most of the energy travels just above the metal, reducing substrate absorption (refs. 3 and 4). The range is excellent for device purposes, typically, 75 to 5000 micrometers at solar frequencies and centimeters in the infrared (refs. 5 to 7). This allows some compromise on materials quality and leaves room to design graduated structures which shift fields into the tunnel diodes, where energy is extracted. For plasmons propagating along the interfaces of the metal-barrier-semiconductor tunnels, the range may be only a few micrometers at the blue end of the spectrum, but this should be adequate.

These properties make surface plasmons ideal for broadband energy transport. Two questions remain: how to couple sunlight into the waves, and how to extract power to do work on a load.

ENERGY CONVERSION

There are three steps in the energy conversion process (fig. 2):

(1) Sunlight excites surface plasmons when its fluctuating electric fields polarize surface charge on the metal. Coherent light is not required, but a prism, grating, or textured surface must be used to provide phase-matching between photons and slightly slower surface plasmons of the same energy.

(2) The surface plasmons transport energy to an array of tunnel diodes, tuned to extract maximum power from waves in a different frequency bands. Diodes differ in geometry and operating voltage, but all share the same materials. The simplest type is an MIS diode formed from the conducting substrate, its native oxide, and a buried or front surface semiconductor electrode.

(3) Energy is extracted by inelastic tunneling, a one-step process in which an electron from the low voltage (semiconductor) electrode simultaneously absorbs a surface plasmon and tunnels to higher potential in the metal. Ideally, the semiconductor bandgap prevents backflow by eliminating unwanted final state energy levels. In a circuit, the tunneling current and load resistance supply the operating voltage. Current flows in the power quadrant as inelastic tunneling raises electrons to higher potential, enabling them to do work on the load.

COUPLING TO SUNLIGHT

Coupling sunlight to surface plasmons poses unique design problems since the light is unpolarized, uncollimated and broadband. Sunlight can excite surface plasmons when fluctuating solar fields polarize surface charge on the conductor. S-polarized photons, which have purely tangential electric fields, can not induce charge on a smooth surface, but "deep" surface texture, on the scale of the wavelength, should allow effective coupling of both polarizations (refs. 8 to 10).

Given charge fluctuations at a surface plasmon frequency, the collective response can not be excited unless parallel momentum is also conserved. Two primary techniques are used to phase-match photons to slightly slower surface plasmons of the same energy:

(1) A slow-wave structure, such as diffraction grating, (refs. 11 to 13) creates photon harmonics with parallel momentum shifted by multiples of the inverse period. When one diffracted order satisifes the phase-matching condition, energy is withdrawn from all orders proportionately. A rough or discontinuous surface (refs. 14 to 19) acts like a superposition of gratings, allowing phase-matching over a broad frequency range.

(2) Alternatively, photons may be slowed by a medium of high refractive index. In a prism-coupler (refs. 20 and 21), phase-matching occurs at specific incidence angles, which typically vary a few degrees across the solar band.

Coupling to surface plasmons is resonant and can be virtually complete in phase-matched structures. As early as 1902, Wood observed anomalies in the scattered light from gratings (refs. 20 to 25) which Lord Rayleigh explained as diffraction into a pair of superficial waves (ref. 26). Fano explained the anomalously large amplitude of the surface wave with an analogy to resonances in a mechanical system (ref. 27). With prism-couplers, 99 percent conversion of monochromatic, p-polarized light to surface plasmons has been demonstrated experimentally on a variety of subtrates (refs. 28 to 30), while experimental evidence for strong coupling on gratings and rough surfaces (refs. 31 to 33 and 34 to 37, respectively) has also been shown.

Since the surface plasmon velocity varies with frequency, a range of grating periods or prism incidence angles is required to couple the solar spectrum. One strategy shown in figure 3 would use a prism or lens to disperse the spectrum over a fixed grating near parallel incidence. Angular dispersion controls the effective grating period and directs the surface plasmons towards appropriately tuned diodes. A guided wave approach appears most compatible with miniature concentrators, since collimation and focusing are required. Requisite periods depend on incidence angles and geometry but visible wavelengths are normally required. Fortunately, perfect collimation and phase-matching are not required as any structure has built-in momentum uncertainty, which is inversely proportional to the parallel dimension.

Alternatively, natural sunlight with a range of incidence angles could be coupled to surface plasmons on a textured surface. This has the virtue of simplicity and potential low-cost for large-area systems without concentration or tracking. Since waves of different frequencies are co-excited without preferred direction, the collecting diodes should be filtered for response to specific frequency bands.

ENERGY EXTRACTION BY INELASTIC TUNNELING

As shown in figure 4, the surface plasmons transport energy to an array of tunnel diodes tuned to extract maximum power from waves in different frequency bands. Although the diodes differ in geometry and operating voltage, all share the same materials. The simplest tunnel diode would be a metal-barrier-semiconductor junction formed from the conducting substrate, its native oxide, and a buried or front surface semiconductor electrode. The metal and semiconductor are at different potentials with the oxide serving as a barrier to inhibit electron flow.

Energy is extracted from the surface plasmons by inelastic tunneling (refs. 38 to 45), a one-step process in which an electron from the low voltage (semiconductor) electrode simultaneously absorbs a surface plasmon and tunnels to higher potential in the metal. The semiconductor is doped heavily p^+, so its Fermi level lies close to the valence band. Thus, almost all the energy can be extracted from surface plasmons with energy slightly more than the operating voltage: the surface plasmon excites an electron from the semiconductor valence band into an empty state just above the metal Fermi level, where there is little excess to be lost to heat.

Ideally, the semiconductor bandgap prevents backflow by eliminating the final state energy levels which could otherwise be reached by conventional elastic tunneling (ref. 45) or by inelastic tunneling with emission of surface plasmons whose energy is less than the operating voltage. Some backflow through surface states and defects is unavoidable.

In a steady-state circuit, load resistance times the net tunneling current results in the impressed voltage across the diode. Current flows in the power quadrant as inelastic tunneling raises electrons to higher potential, enabling them to do work on the load. Since the diode voltage determines the fraction of surface plasmon energy extracted, the load should be regulated to maintain constant voltage as the current varies with solar flux.

PRECEDENT: TUNABLE LIGHT-EMITTING DIODES

Tunable light-emitting diodes based on inelastic tunneling were first demonstrated in 1976 by Lambe and McCarthy (refs. 47 to 49). The fabrication is straight-forward (refs. 50 to 56): A thin film of aluminum is evaporated on a glass or ceramic substrate, encouraged to form the native oxide, and crossed with a counter-electrode, typically 200 Å of silver, to form a tunnel junction of millimeter-square area. A voltage is applied across the junction to cause inelastic tunneling with emission of surface or junction plasmons. These waves can radiate visible light if phase-matching is provided by roughening the electrode surface with chemical etches, abrasion, or deposition of small metallic particles or by growing the whole diode structure on an irregular surface (e.g., CaF_2 islands) or a holographic grating. When the voltage is varied from 2 to 4 volts, the color changes from red through blue-white, with uniform glow across the outer electrode surface. Although still extremely inefficient, these are room temperature, reasonably stable devices with intriguing prospects for thin film video displays.

In present LED's, the glow can only be seen in a dark room - implying efficiencies less than 10^{-5} percent. What went wrong? The applied voltage

causes a current of tunneling electrons which have a very high (order one) probability to excite slow junction plasmons, which propagate along the tunnel interfaces (refs. 38 to 40). Unfortunately, most of the junction plasmons are absorbed by the substrate before they can radiate through the silver electrode. The mean free paths for substrate absorption and radiation differ by five orders of magnitude, which seems to explain the low efficiency (refs. 38 to 40). When diodes are grown on visible frequency holographic gratings (refs. 55 and 56), the plasmons are emitted on the outer electrode surface where they can radiate effectively. This time the efficiency is low (10^{-5} percent) due to weak coupling to the tunneling electrons (ref. 57).

The situation should be easier for photodiodes than it is for LED's, since the controlling mean free paths are different. Surface plasmons can be efficiently excited by light. Their long range leaves room to design graduated structures which shift fields into the tunnels. Alternatively, phase-matching structures might be used to link surface and junction plasmons through some type of bulk mode. Both techniques are used with high efficiency, nearly 100 percent in some cases, for closely related surface acoustic wave devices (refs. 58 to 60). Junction plasmons have shorter range, typically a few micrometers, but preliminary calculations from a Berkeley grant suggest a comparable range for junction plasmon capture by tunneling electrons. This would be a good starting point for efficient diodes; however, quite a bit more theoretical modeling and experimental characterization is necessary before we are confident of our understanding of processes occurring in the tunnel diodes.

CLOSING REMARKS

This paper has introduced an advanced concept for direct conversion of sunlight to electricity, which aims at high efficiency by tailoring the conversion process to separate energy bands within the broad solar spectrum. The objective is to obtain a high level of spectrum-splitting without sequential losses or unique materials for each frequency band. In this concept, sunlight excites a spectrum of surface plasma waves which are processed in parallel on the same metal film. The surface plasmons transport energy to an array of metal-barrier-semiconductor diodes, where energy is extracted by inelastic tunneling. Diodes are tuned to different frequency bands by selecting the operating voltage and geometry, but all diodes share the same materials.

Surface plasmons should lend themselves to an exciting new class of electro-optic devices, operating over a broad frequency range (IR through UV). The waves can be supported on common metals, like aluminum or silver, with only a thin film required. This allows extremely lightweight systems for space use, or materials-conservative devices on low-cost substrates for terrestrial applications. The long surface plasmon range allows some compromise on materials quality and leaves room to design graduated structures which shift fields into the tunneling region. Surface plasmons have strong coupling to both light and tunneling electrons; the challenge will be to accomplish both in the same device.

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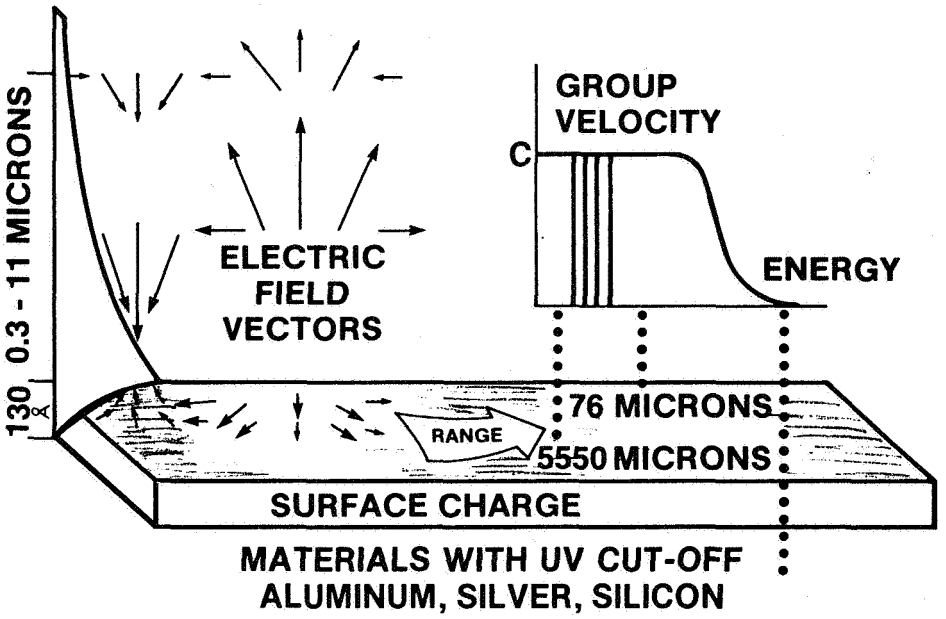


Figure 1. - Surface plasma waves.

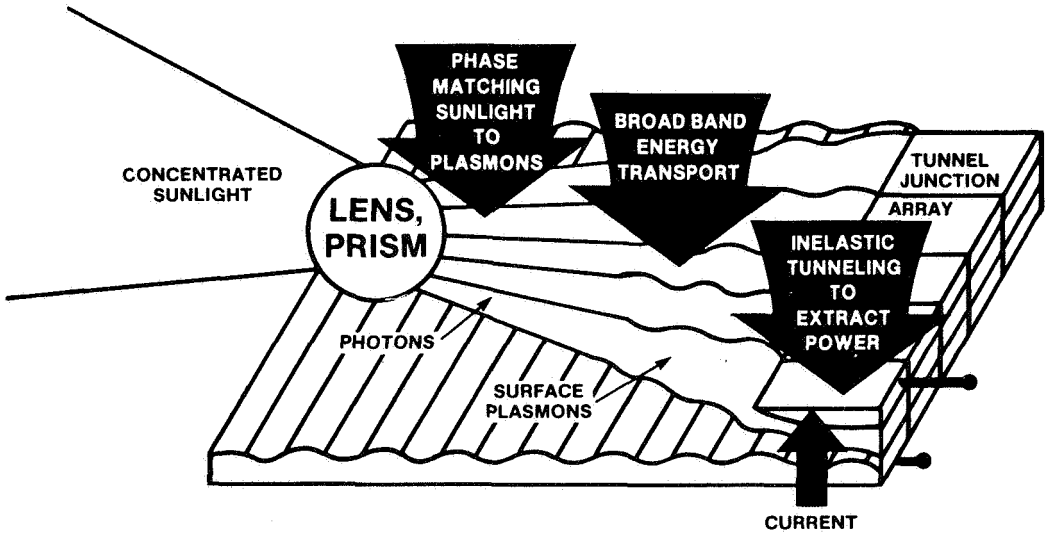


Figure 2. - Parallel processing with surface plasma waves.
Status: early conceptual phase.

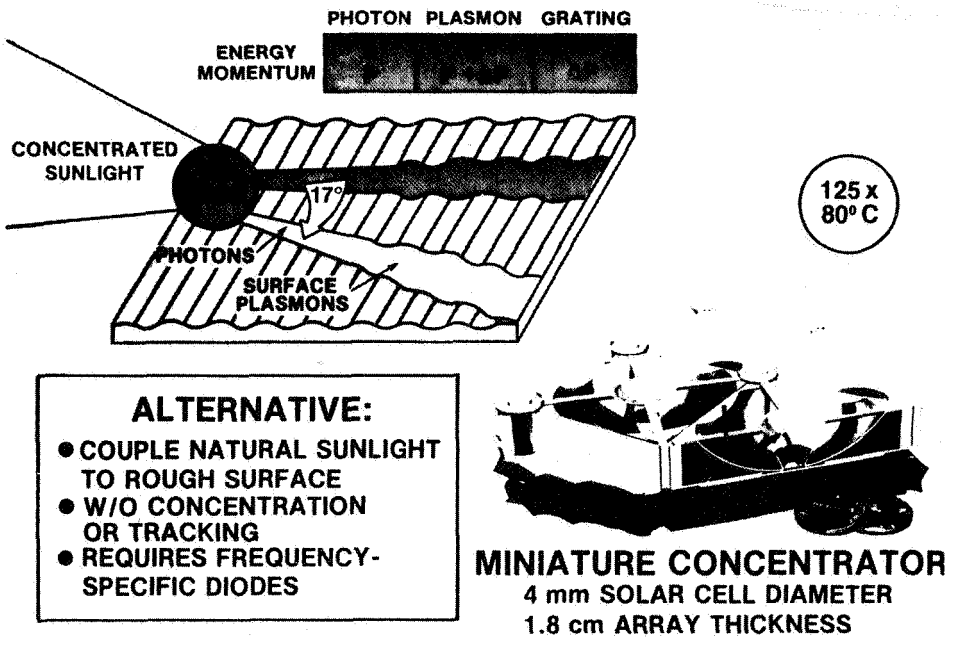
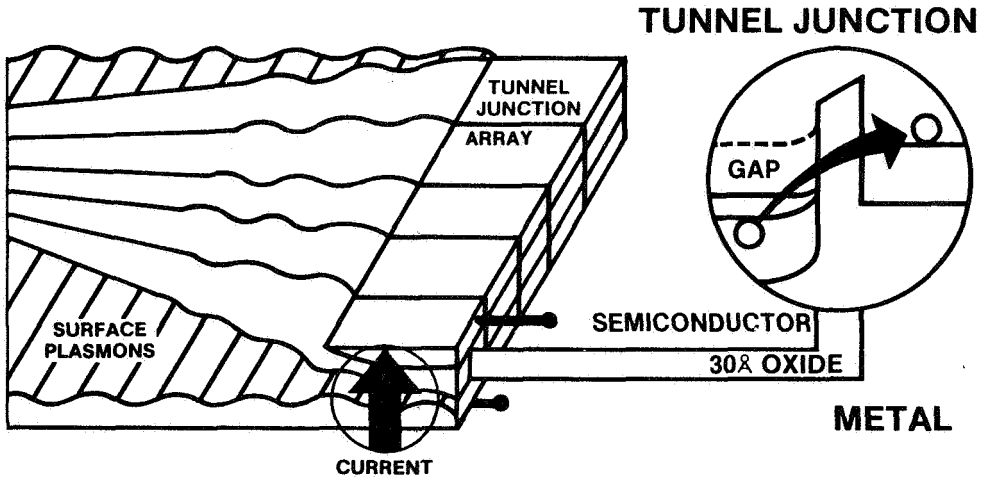


Figure 3. - Coupling to sunlight.



- INELASTIC TUNNELING ABSORBS PLASMONS TO PUMP ELECTRONS TO HIGHER POTENTIAL
- VOLTAGE SUPPLIED BY TUNNEL CURRENT AND LOAD RESISTANCE
- SEMICONDUCTOR BANDGAP LIMITS BACKFLOW

Figure 4. - Extracting power from surface plasmons.

STUDY OF GaAs DAMAGE COEFFICIENTS

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The development of GaAs solar cells has advanced to the point where it can be considered as a potentially enabling technology for a range of future missions. Since an adequate set of radiation characterization test data for GaAs solar cells does not exist, the sparse existing solar cell data was combined with general GaAs device radiation damage coefficients reported in the literature. These damage coefficients were then applied to GaAs solar cell radiation damage analysis for a number of characteristic orbits. The study showed that for orbits where penetrating electron radiation dominates, GaAs damage is similar to Si damage. However, in orbits where damage from lower energy protons dominates, the degradation of thinly shielded GaAs cells is more severe than the damage of equally shielded Si cells, while the degradation of thickly shielded GaAs cells is less severe than the degradation of equally shielded Si cells. The most significant conclusions from the study are that (i) the damage-equivalent 1-MeV fluence for GaAs is, in general, different from that for Si cells for the same shielding thickness, same orbit and same orbital exposure time, and (ii) the damage coefficients of GaAs cells are functions of total accumulated fluence, indicating a reduced rate of damage as the fluence increases.

CURRENT STATUS OF THIN-FILM CLEFT GaAs SOLAR CELLS*

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Single-crystal GaAs layers as thin as 5 m have been grown and separated from reusable GaAs substrates by the CLEFT process. This process has been used in fabricating a 17% (AM1) GaAs solar cell, only 10 m thick, that is bonded to a glass substrate. The procedure for preparing CLEFT cells will be described. The thin-film technique eliminates the cost and limited availability of GaAs as major obstacles to utilization of GaAs solar cells. In addition, by using CLEFT cells with lightweight packaging it should be possible to produce panels with specific power of several kW/kg. The potential utilization of CLEFT cells in a high-efficiency tandem-cell structure will be discussed.

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