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Lithographic Antennas for Enhancement of Solar-Cell Efficiency

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Lithographic Antennas for Enhancement of Solar-Cell Efficiency

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ABSTRACT

This report documents proof-of-concept demonstration of the use of lithographic antennas for enhancement of solar-cell efficiency. A micro-sized lithographic antenna array was theoretically modeled, designed and fabricated. Experimental research was performed to validate the ability of the antenna array to concentrate infrared and visible energy onto photovoltaic (PV) materials. The research will serve as the basis for the design of a miniature power source for remote sensors.

SUMMARY

The purpose of this project is to fabricate an array of micro-sized lithographic antennas and to experimentally validate their ability to concentrate infrared and visible energy onto photovoltaic (PV) materials. This will make it possible to design a miniature power source for remote sensors. Accomplished tasks include: 1) Formalize a research collaboration with the University of Central Florida's Center for Research in Electro-Optics and Lasers, 2) Design an antenna array, 3) Fabricate a prototype antenna array at Cornell University's National Nanofabrication Facility and 4) Perform a proof-of-concept demonstration to verify the enhanced absorption of an antenna-coupled thin-film Si layer, compared to a similar layer without antennas. This work was performed in behalf of the Department of Energy, NN-20, Phase One Advanced Concepts.

This research has resulted in several potential technology applications, including: 1) Continuation of this line of research will ultimately lead to the viability of thin-film techniques for fabrication of photovoltaic (PV) solar cells, 2) Antenna-coupling techniques promise to provide higher solar cell output power within a given mass and weight. Antenna-coupling can also reduce costs for exotic PV materials, such as bandgap-engineered semiconductors, which are sometimes required to meet power density requirements. The antenna thin-films would result in less performance degradation with long-term radiation exposure. These characteristics would be a distinct advantage for small, land-based power sources for remote, unattended-sensing applications, as well as for space-based systems, where launch costs scale dramatically with payload weight and 3) There is a significant potential for crossover of microantenna-array technology to countermeasures applications at longer wavelengths in the thermal infrared regions. Potential applications include the development of chameleon surfaces, i.e., surface treatments that allow a tailored, or even a dynamically controlled IR signature. Arrays of IR microantennas on the exterior surface of a vehicle, or projectile, could be designed to reduce the object's emission in the portion of the IR band for which the atmosphere is transparent to IR radiation, and enhanced in the portion of the IR band for which the atmosphere is opaque, leading to the development of IR "stealth" coatings.

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Lithographic Antennas for Enhancement of Solar-cell Efficiency

INTRODUCTION

The project objective was to demonstrate an enhanced absorption at solar wavelengths of an antenna-coupled thin-film silicon layer, compared to a similar layer without lithographic antennas. The microantenna arrays were fabricated on thin silicon film and their absorption properties were experimentally characterized. The antenna-arrays were fabricated using electron-beam lithography at the Cornell Nanofabrication Facility (CNF), a user facility supported by the National Science Foundation. The computer-aided design of the microantenna array and the absorption measurements were performed under contract by the Center for Research & Education in Optics & Lasers (CREOL) at the University of Central Florida.

Experimental Results

We measured a 31% increase in absorption of focused white light by the use of a microantenna array on the silicon surface, for radiation polarized parallel to the antenna arms, compared to an adjacent region of the substrate without antennas.

Figure 1. Enhanced absorption of antenna-coupled Si film (light polarized parallel to antenna).

The proof-of-concept objective of this phase of the research has been successfully met: verification of an enhanced absorption at solar wavelengths of an antenna-coupled silicon layer, compared to a similar layer without lithographic antennas.

This result enables the effective use of thin-film techniques for fabrication of photovoltaic (PV) solar cells. Presently, thin Si films are not used in PV cells, because the small absorption of indirect-bandgap materials require film thicknesses that can not be fabricated as mechanically stable films.

Antenna-coupling techniques give the absorption characteristics of thick substrates in very thin silicon layers. Compared to the present method of sawing and polishing wafers from silicon boules, thin-film FV cells will have the following significant advantages:

- More power-efficient manufacturing processes and use of semiconductor materials
- Less performance degradation with long-term radiation exposure
- Higher, more uniform conversion efficiency across solar spectrum, resulting from a uniform photon-penetration distance regardless of wavelength
- Higher power output within a given mass, weight, and volume budget.

SUBSTRATE DESIGN

Our antennas were fabricated on an etched silicon membrane (Nanostructures, Inc., Santa Clara, CA), with a thickness of approximately 3 microns. The base wafer was of standard thickness (385 microns), initially polished on the top surface. A 4-by-4 matrix of separate 1-cm membrane regions was electrochemically etched to the desired thickness. The antennas were fabricated on the polished top side of the membrane. The texture of the etched underside of the membrane was slightly rough, with about 1000 Angstrom rms roughness (manufacturer spec). The antennas were designed assuming illumination through the membrane.

We decided on the thinned-membrane approach, after consideration of various options including fabrication of thin films of silicon on quartz, because it provided commercially-available silicon films that were thin enough to be translucent at visible wavelengths. Use of membranes rather than films supported on a dielectric substrate was also appealing because minimizing the number of material interfaces simplifies interpretation of the measurements. As noted in the introduction, the measured optical characteristics of the silicon membranes (without antennas) were 25% transmission, 40% reflection, and 35% absorption, when illuminated from the etched side with focused visible light from a microscope.

Designs in previous research phases were based on the use of crystalline silicon, with a 90% absorption in 380 microns, which implies an attenuation coefficient of 60 cm^{-1} . This represents the usual situation for silicon wafers where absorption is calculated near the cutoff wavelength of 1 micron (photon energy equal to the silicon bandgap of 1.24 eV). Using this attenuation coefficient, we predicted an absorption of 6% for a 10-micron-thick film alone, and a 39% absorption for an antenna-coupled film. We measured absorption of 35% for our 3-micron-thick film (corresponding to an attenuation coefficient of 2000 cm^{-1}), and an absorption of 46% for the film with antennas.

Absorption Measurement Theory

The attenuation coefficient $\alpha(\lambda)$ in silicon is a strong function of wavelength, as seen in Fig. 2. An attenuation coefficient of 2000 cm^{-1} is typical for photon energies of 1.9 eV (a wavelength of 0.65 microns). The lamp we used in our measurements was a tungsten filament, approximating a 2800-K blackbody source. This lamp has a substantial portion of its power output in the visible portion of the spectrum, which weights the measurement toward larger attenuation coefficients. The absorption "A" is a function of film thickness and experimental setup. Absorption is given by:

$$A = \frac{\int_{\lambda_1}^{\lambda_2} (1 - e^{-\alpha(\lambda)L}) \phi_{\lambda, \text{source}}(\lambda) \mathcal{R}_{\text{det}}(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} \phi_{\lambda, \text{source}}(\lambda) \mathcal{R}_{\text{det}}(\lambda) d\lambda}$$

(1)

where λ_1 is the lower limit of the measurement spectral passband (in the ultraviolet, caused by the glass envelope of the lamp), λ_2 is the upper limit of the measurement spectral passband (around 1.1 microns. caused by the response of the silicon CCD detector), $\phi(\lambda)$ is the spectral flux from the lamp (Watt/micron), and $\mathcal{R}(\lambda)$ is the spectral responsivity of the CCD detector (Volt/Watt).

Hence, for a given set of measurement conditions, the actual absorption of the film can be measured unambiguously. Measurements verified an enhanced optical absorption using microantennas.

Figure 2. Attenuation coefficient for silicon at room temperature.

Substrate Impedance Effects

The sheet resistance of the bulk portion of the wafers used for the membranes was measured to be 10 ohms/square/75um, confirming the manufacturer's specification. The main portion of the conductivity of the bulk wafer is concentrated in a thin heavily-n-doped layer. The supporting lightly-doped p region does not contribute significantly to the conductivity. The electrochemical etching process leaves only the thin n-doped layer of the silicon, so the membrane sheet resistance should be approximately the same as

that of the bulk wafer. It is not possible to measure sheet resistance of the 3-micron thick membrane directly with a standard 4-point-probe technique.

The impedance of an individual half-wave dipole antenna on a dielectric slab of permittivity ϵ_r (11.8 for silicon) is given by

$$R_A = \frac{R_{\text{dipole, free space}}}{\sqrt{\frac{1 + \epsilon_r}{2}}} = \frac{73 \text{ ohm}}{2.53} = 29 \text{ ohm} \cdot \quad (2)$$

while the load impedance presented across the feed of the antenna is the sheet resistance of the membrane in parallel with the impedance of free space

$$\left(\frac{1}{R_{\text{sheet}}} + \frac{1}{R_{\text{free-space}}} \right)^{-1} = \left(\frac{1}{10} + \frac{1}{377 \text{ ohm}} \right)^{-1} = 9.7 \text{ ohm} \cdot \quad (3)$$

The membranes we used did not provide an optimum impedance match to the antennas, as is evident in the antenna impedance of 29 ohms compared to the load impedance of the membrane of 9.7 ohms. However, the commercial membranes were adequate for proof of concept demonstration. Membranes, with special doping to obtain higher sheet resistance and a more optimum impedance match are available by special order, but costs were prohibitive under current funding levels. An experimental study of antenna coupling efficiency, as a function of substrate sheet resistance, would be valuable in the next phase of this research.

ANTENNA DESIGN

The design used for the proof-of-concept was an array of dipole antennas, shown schematically in Fig. 3. This basic array was repeated over a 75-micron-by-75-micron area of the substrate, so that optical measurements could be conveniently performed. As discussed in the next section, 125 separate 75-micron-by-75-micron antenna arrays were fabricated on the membrane to assure proper electron-beam dosage for exposure of the electron photoresist. Each 75-micron-by-75-micron antenna array contains approximately a 600-by-1500 matrix array of antennas.

The antenna metal was aluminum of 50-nanometer thickness. The antenna arms were ovals of 30-nanometer minimum axis and 60-nanometer maximum axis. There was a 30-nanometer feed gap between adjacent arms of the antennas, and a 50-nanometer gap between adjacent antennas in both the horizontal and vertical directions on-chip.

The basic oval shape and array layout of the antennas is illustrated with a series of electron-beam photographs (in reflection). The antenna-array layout is shown in Figure 4, at a magnification of 300,000x, Figure 5 at 60,000x and Figure 6 at 800x. The low magnification (wide field of view) of Figure 6 is not sufficient to resolve the individual antennas that are obvious in the previous photos, so the 75-micron by-75-micron antenna array appears to be a region of contiguous metallization.

Figure 3. Antenna-array design configuration.

Figure 4. Antenna array at 300,000x magnification, showing oval geometry.

Figure 5. Antenna array at 60,000x magnification, showing array configuration.

Figure 6. Antenna array at 800x magnification, showing regions of contiguous metallizations.

Modeling Results

The absorption of the antenna-coupled film, as a function of gap spacing and sheet resistance, was investigated using a combination of commercial and military software packages. The IE3D software developed by Zeland, Inc. was used in conjunction with the Periodic Moment Method (PMM) Code developed by the US Air Force under contract to Ohio State University. Special permission was obtained from USAF for the use of the PMM code on this project. Our modeling showed that absorption is enhanced, for a typical range of sheet-resistance values, when the inter-arm feed gap is as small as possible, consistent with the resolution of the electron-beam lithography. The impedance matching between the feed resistance and the antenna impedance determined whether the metal ovals acted as independent dipoles or as arms of a longer dipole antenna. For the 30-nanometer feed gap used, there was significant interarm cross coupling. A smaller feed gap would be desirable to reduce cross-coupling effects. Current electron-beam instruments present a manufacturing limitation, however, discussions with CNF personnel indicate that a feed-gap dimension of 20 nanometers is possible in the near term.

Antenna Wavelength Optimization

For a silicon substrate, the antennas have a stronger reception of radiation by about a factor of 40 when illuminated from the dielectric side, so the dielectric wavelength is the pertinent design wavelength. The length of the resulting dipole antennas was intended to be one-half wavelength for radiation of 1 micron free-space wavelength, and full-wave for radiation of freespace wavelength of 0.5 micron. Using a 0.5-micrometer design wavelength, and a silicon refractive index of $n = 3.4$, yields a dielectric wavelength ($\lambda_d = \lambda_{\text{free-space}}/n$) of 150 nanometers. This design was consistent with the 30-nanometer resolution capabilities of the Leica VB-6 electron beam machine used at CNR

ANTENNA FABRICATION USING LITHOGRAPHY

We used a dose-matrix procedure to establish proper e-beam current and exposure time for the photoresist. At each dosage, a 75-micron-by-75-micron chip area was exposed. The field of view of the Leica VB-6 electron-beam writer was 25 microns, so each dose trial consisted of nine 25-micron-by-25-micron squares located contiguously to make a 75-micron-by-75-micron square. Within a properly exposed 75-micron square, there are subtle differences (on the order of a few percent in optical transmission) between the optical properties of the 25-micron subsquares. These can be seen in the electron-beam micrograph of Figure 6. These variations are caused by small variations in the electron-beam current as the beam moves to its new field of view. These variations have largely been corrected by CNF staff during subsequent maintenance and adjustment procedures for the Leica VB-6.

Overall a dose matrix of 125 75-micron squares was exposed on the silicon membrane. This dose matrix is seen in an optical micrograph (50 x, in reflection) as Figure 7. The arrow on the photograph highlights the 75-micron square that had the optimum exposure, and the best optical absorption enhancement.

For exposures which were not of sufficient dosage, it can be seen in Figure 7 that there is an increased variability in some of the adjacent 25-micron squares. This variation is seen more clearly in Figure 8, which is an electron micrograph in reflectance at a magnification of 25,000 x. Figure 8 clearly shows incomplete adhesion of underexposed antennas. For regions of the dose matrix that had excess exposure, the antennas tended to coalesce into a continuous metallization.

The antenna array shown in the electron micrograph of Figure 6 (the optimum exposure indicated by an arrow in Figure 7) formed the basis for our optical-absorption measurements.

Figure 7. Electron micrograph of antenna array at 50x in reflection. the optimum-exposure zone is indicated by an arrow.

Figure 8. Electron micrograph of substrate that shows incomplete adhesion of underexposed antennas.

OPTICAL-ABSORPTION MEASUREMENTS

Figure 9 shows an optical micrograph (in transmission) of the same 75-micron-by-75 micron region seen in Figure 6. The magnification in Figures 6 and 9 are the same (800 x). The portion of the substrate with the antenna array clearly absorbs more visible light than does the surrounding substrate, which appears lighter. The striations seen in the substrate are the rough surface of the etched side of the membrane, seen slightly out of focus, since the micrograph of Figure 9 was focused on the top (smooth) surface of the membrane on which the antennas were fabricated. The small subcell transmittance variations seen in Figure 9 are the result of the variations in electron-beam dosage seen (in reflection) on the electron micrograph of Figure 6. The vertical banding structure seen in Figure 9 is an aliasing artifact caused by the fact that the antenna-array pattern has a higher spatial frequency than can be resolved by the CCD camera used to acquire the optical micrographs.

The transmission and reflection of the silicon membrane were measured under a 40-power optical microscope (with a 20-power relay lens to the CCD for a total magnification of 800 X), in focused white light from a 2800 K tungsten lamp, for two linear polarizations: polarization parallel to and perpendicular to the antenna arms. Transmittance measurements were made with upward illumination, and reflectance measurements were made with downward illumination on a standard Nikon microscope. The orientation of the surface being measured was adjusted so that the antennas were always illuminated through the silicon substrate. The absorption A of the membrane was calculated from measured data for reflection R and transmission T using the power-balance equation:

$$A=1-T-R$$

(4)

We calibrated the linearity and repeatability of the measurement system using commercial step-wedge targets of known (and independently measured) reflection and transmission.

From the theory of elementary dipole antennas, one expects an enhanced absorption for radiation polarized along the arms of the antenna, since for that polarization, current waves will be induced to flow longitudinally along the arms by the incident electric field. Indeed, the enhancement of absorption was seen only for the parallel-polarized radiation. Measurements for radiation polarized perpendicular to the antenna arms did not show an increase in absorption for substrates with antenna arrays.

The results of the measurements were shown in Fig. 1. For radiation polarized parallel to the antenna arms, the absorption of the antenna-coupled silicon membrane was 46%, compared to 35% for adjacent regions of the membrane without the antenna array. Thus, the measurements show a 31 % increase in absorption of the silicon film using the microantenna array.

The proof-of-concept objective of this phase of the research was successfully accomplished: verification of an enhanced absorption at solar wavelengths of an antenna-coupled silicon layer, compared to a similar layer without lithographic antennas.

Figure 9. Optical micrograph of 75 μm x 75 μm region. Antenna arrays absorb more visible light as indicated by dark region.

SIGNIFICANCE OF RESEARCH

This section discusses the potential technology enhancements that can be realized from further application of lithographic antennas.

Economical Use of Thin-film

Continuation of this line of research will ultimately lead to the viability of thin-film techniques for fabrication of photovoltaic (PV) solar cells. Presently, thin Si films are not used in PV cells, because the small absorption of indirect-bandgap materials require film thicknesses that can not be fabricated as mechanically stable films.

Antenna-coupling techniques make possible the absorption characteristics of thick substrates in very thin silicon layers. Use of thin-film fabrication techniques for production of solar cells will have the following advantages over the current technology of sawing and polishing wafers from silicon boules.

- More power-efficient manufacturing processes and use of semiconductor materials
- Less performance degradation with long-term radiation exposure
- Higher, more uniform conversion efficiency across solar spectrum, resulting from a uniform photon-penetration distance regardless of wavelength
- Higher power output within a given mass, weight, and volume budget.

Miniature Power Applications

Component-performance improvements along these lines for solar PV cells will benefit those systems requiring long-lifetime, miniaturized power-generation systems. In the near term, these characteristics would be a distinct advantage for small, land-based power sources for remote, unattended-sensing applications, as well as for space-based systems, where launch costs scale dramatically with payload weight.

Antenna-coupling techniques can also reduce costs for exotic PV materials such as bandgap-engineered semiconductors and multiple-element stacks by reducing the amount of material used. A sparse array is possible where islands of specialized materials are used for the photoconversion, and antennas are used to increase the collection cross-sectional area beyond the actual area of the islands.

Counter-Measure Applications

There is also a significant potential for crossover of this microantenna-array technology to countermeasures applications at longer wavelengths in the thermal infrared (3 - 5 micron and 8 - 12 micron). The arrays fabricated for this project were designed for wavelengths in the visible and near-infrared range. Fabrication of longer-wavelength structures relaxes the lithographic tolerances required, and the functionality of the arrays will be unchanged for a given ratio of structure size to wavelength. An important application is the development of chameleon surfaces, i.e., surface treatments that allow a tailored, or even a dynamically controlled IR signature. Current research has concentrated on optimization of absorption. Absorption and emissivity are equal because of Kirchoff's Law, so

emissivity is within the control of the antenna-array design. Arrays of IR microantennas on the exterior surface of a vehicle, or projectile could be designed to reduce the object's emission in the portion of the IR band for which the atmosphere is transparent to IR radiation, and enhanced in the portion of the IR band for which the atmosphere is opaque, leading to the development of IR "stealth" coatings. At wavelengths of 10 microns, previous research has demonstrated polarization tuning of single-element antennas by application of a small bias voltage. Arrays of these elements can be envisioned for which a single control voltage might change the spectral emissivity or the polarization signature for an extended target.

PROPOSED FUTURE RESEARCH

It is proposed that the following tasks be performed to continue development of lithographic antenna solar cells. Each task could lead to commercial implementation of the technology.

Validate That Absorption is a Function of Photogeneration

For near-term PV applications, the most important issue to prove next is that the increased absorption is caused by an enhanced rate of photogeneration of electron-hole pairs (EBPs) in the fringe-field region of the antennas. Fabrication of photocells with external electrodes as shown in Figure 10 will allow measurement of the photoconductivity of the cells with and without the antennas. If the increased optical absorption that was observed is indeed caused by an enhanced EBP-generation rate, the antenna-coupled photocells will show a correspondingly higher change in conductivity under illumination. Fabrication of these photocells is well within our capabilities in collaboration with the CNF.

Figure 10. Proposed antenna-coupled photocell, for verification of enhancement of electron-hole-pair generation rates by microantennas ($I_{with-ant} > I_{w/o-ant}$)

Optimize Impedance Matching of Antenna to Solar Cell

A parameter study should be made of the effect of substrate sheet resistance on the absorption efficiency for a given antenna design. The cost and lead time involved with this aspect were outside of the scope of this phase of the research, but potential absorption gains of a factor of two should be possible beyond those already observed by proper impedance matching between the antenna and the membrane. This study would probably involve fabrication on three different sheet resistances, in order to assess trends in absorption behavior.

Evaluate Other Antenna Configurations

Antenna designs should be investigated that exhibit enhanced absorption for unpolarized light, since efficient use of sunlight requires polarization-independent antennas. A logical design to investigate initially would be an array of tripoles as seen in Figure 11, with 3 conductive arms separated by 120 degrees in angle. Tripoles are known to have nearly polarization-independent behavior. We have appropriate numerical-electromagnetics capabilities for modeling and optimization for these structures.

Figure 11. Tripole Antenna Array.

Perform Wavelength Resolved Measurements

Wavelength-resolved absorption measurements should be made that will allow a detailed comparison with both antenna theory and the spectral dependence of the material absorption. In the current phase of the research only white-light measurements were performed. Fourier-transform (FTIR) spectrometers available in the visible and near-IR portion of the spectrum do not generally have the spatial resolution required for 75-micron sample sizes. A FTIR spectrometer would have to be modified with components (source, optics, and filters) to spectrally resolved measurements at these spatial resolutions.

CONCLUSIONS

A proof-of-concept demonstration that micro-lithographic antennas can be used for enhancement of solar-cell efficiencies has been successfully completed. A technical path forward has been presented for optimization and integration of the solar array into a product. Several other potential technology applications have been identified. It is recognized that photovoltaic solar cells have a potentially large application base, and novel techniques that lead to higher performance cells and cost-effective PV manufacturing alternatives would have considerable intellectual-property value. Appropriate measures have been taken to protect the technology through patent disclosures. Parallel technologies are under development (i.e. embossing techniques) that will allow low-cost replication of electron-beam-fabricated surfaces, reaching cost targets for entry into the larger solar-PV Marketplace.