Yagi-Uda Nanoantenna Structures for Infrared Detection Using Silicon

William T. Rieger Jr.*, Jean J. Heremans*, Hang Ruan†‡, Yuhong Kang† and Richard O. Claus†
*Department of Physics
Virginia Tech, Blacksburg, Virginia 24061
Email:wrieger@vt.edu
†NanoSonic Inc. Pembroke, VA 24136
‡Department of Mechanical Engineering
Virginia Tech, Blacksburg, Virginia 24061

***Abstract*—Detection of light below band gap energies using nanolithographic Yagi-Uda antennas is discussed. Two nonlinear mechanisms contributing to generation of photocurrent are identified and evaluated. Results of a Si near-IR photodetector are presented and application to mid-IR discussed. Additionally, finite element modeling methods are employed.**

I. Introduction

Nanoantennas have been used successfully to increase photodetection beyond the limits of semiconductor material properties. [1][2][3][4]This above band gap detection is possible because of the plasmonic nonlinear conversion of incident radiation; this nonlinear process is responsible for high reported quantum efficiencies. The nonlinear photocurrent generation is caused by at least two phenomena—"hot" electron injection[2] and higher harmonic reradiation.[5][6] When incident light excites surface plasmons in the antenna structure, they may decay along a number of pathways, some of which contribute to the photocurrent. Resonant surface plasmons are capable of transferring large amounts of kinetic energy to valence electrons within the metal—resulting in hot electrons. If these electrons exhibit energies above the metal-semiconductor interface barrier energy then the hot electrons are free to move into the semiconductor. Resonant surface plasmons may also decay by reradiating. The frequency of this reradiated light can be the same as the plasmon resonance or an integer multiple of the original frequency. In this manner near-IR photons are converted to visible via second harmonic reradiation and mid-IR radiation can be converted to visible via third or fourth harmonic reradiation. Here, a Si based Metal-Semiconductor-Metal (MSM) photodiode is used concurrently with an array of 400 nanolithographic Yagi-Uda antennas; an example of these is depicted in Figure 1. The resulting wavelength selectivity and directivity are engineered in the near IR with photon energies below the band gap of Si. Current limiting factors for nanoantenna structures center around the tendency of surface plasmons to decay along pathways that do not contribute to the photocurrent.

II. Methods

Nanoantennas are frequently fabricated on transparent surfaces and interrogated using purely optical methods. Here an electrical interrogation method is employed where the nanoantennas are used as a sensitizing agent in the semiconductor region of a MSM structure. This method uses hot injection methods similar to the ITO-based measurement scheme, however represents a simplification requiring only a metallic monolayer on a silicon substrate. In addition to hot electron injection, second and third harmonic generation may contribute to the measured photocurrent. Electrical characterization of nanoantennas in realistic environments is a necessary step towards their useful application; testing in real life conditions is necessary because much like their RF counterparts, nanoantennas are affected by their environment. In particular the introduction of a dielectric/semiconducting substrate serves to shorten the effective wavelength.

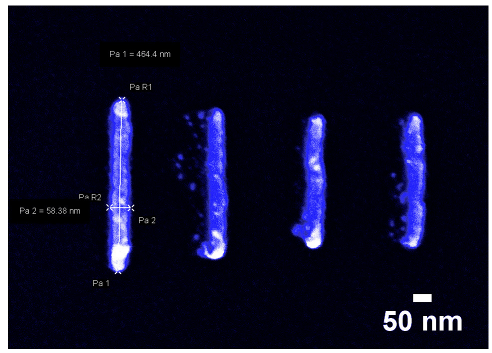

Fig. 1. Single nanolithographic Yagi-Uda antenna. Design and actual dimensions are given in Table I. The measured device includes an array of 400 such devices between the electrodes of a Metal-Semiconductor-Metal photodiode.

A. Fabrication

Devices were fabricated on n-Si $< 100 >$ from which a protective oxide layer was removed using 6:1 buffered oxide etch. A simplified MSM structure was fabricated using photolithography. Thermal evaporation and lift-off were used to obtain 10 nm Cr and 50 nm. Following deposition of the MSM structure an array of 400 Yagi-Uda antennas was patterned using electron beam lithography. Cr/Au was deposited in the same manner as the previous step, leaving a metallic monolayer on the surface of the Si substrate.

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TABLE I

DESIGN AND FABRICATED DIMENSIONS FOR ANTENNAS WITHIN AN ARRAY. ELEMENTS ARE 60 NM HIGH AND MEASURED DIMENSIONS HAVE UNCERTAINTY $\pm$ 5 NM.

Element	Design Lengths (nm)	Measured Lengths (nm)
Reflector	443	464
Detector	388	406
Director	345	357
Element Spacing	258	264
Element Width	50	58

B. Experimental Setup

Characterization of the antenna array involved use of optical and electrical methods. Optically a collimated white light source was used concurrently with a monochromator from a spectroscope. The output of the spectroscope emitting monochromatic light was directed to be incident to the sample. A 17 Hz chopper was placed in the optical pathway before the monochromator. A stage was fabricated to allow the angle of incidence of light on the sample to be adjusted in the plane orthogonal to the length of the antenna elements. Electrically, the fingers of the MSM photodiode were biased at 1 VDC and the photocurrent was measured using lock-in detection referenced to the chopper. Measurements were obtained at two angles of incidence; glancing—where incident light was aligned with the directivity of the antennas—and 45 degrees—where the incident light was sufficiently far from the antenna directivity to reduce the antenna effect.

C. Finite Element Modeling

In order to predict nanoantenna behavior and calculate effective wavelengths more accessibly, finite element modeling has been used. Modeling efforts use COMSOL Multiphysics Wave Optics Module. Modeled results are solved for in the frequency domain, using a range of angles of incidence and polarization orientations. Material properties are modeled using the Lorentz-Debye model. Preliminary results indicate clear resonances of the modeled structure.

III. RESULTS

Two resonance peaks were identified in the glancing results at 1110 nm and 1690 nm, as observed in Figure 2. These resonances have a harmonic relationship that is consistent with effective wavelength theory.[7] Results at a 45 degree angle do not exhibit these resonances, consistent with the expected Yagi-Uda directivity.[4] Estimated quantum efficiencies are 5.1% and 3.1% for the two resonance peaks, respectively. The non-optimal quantum efficiencies are likely due to the decay of plasmons along pathways that do not contribute to the photocurrent; current research efforts are focused on this aspect.

IV. CONCLUSION

Nanoantennas represent a method of utilizing nonlinear plasmonic effects to generate photocurrent from below bandgap energy photons. While current work has focused on near-IR where second harmonic generation is sufficient to reach band gap energies, further efforts focus on more efficiently generating third and fourth harmonics allowing mid-IR detection using nanoantennas. Similarly, nanoantenna structures can be employed as novel materials effectively decreasing the band gap energies by a factor of 2 based on second harmonic generation. In addition to reradiation of higher harmonics, hot electron injection also contributes to the photocurrent. Current/future work in this area involves using finite element methods (COMSOL Multiphysics) to computationally determine effective wavelength for realistic structures.

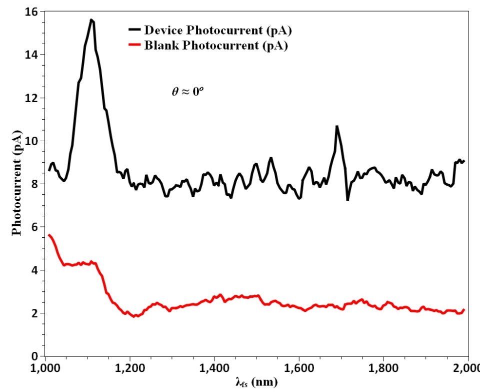

Fig. 2. Results of device illuminated at a glancing angle. The device includes an array of 400 Yagi-Uda nanoantennas as in Figure 1, oriented in such a way that the electrodes do not cast a shadow on the device. Measurements were obtained at a bias of 1 VDC. A "blank" device was also fabricated lacking only the antenna array. Clear resonances can be observed at 1110 nm and 1690 nm

ACKNOWLEDGMENTS

The authors would like to thank Robert Romanofsky for many helpful discussions.

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