Engineering of plasmonic effects in photodetectors and high-efficiency photovoltaics

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***Abstract*-Integration of metal and dielectric nanostructures with semiconductor-based devices offers new opportunities for engineering the performance of high-efficiency photovoltaics and of photodetectors generally. We discuss here approaches in which plasmonic and related scattering effects are exploited to enable efficient coupling of photons into optical waveguide modes of semiconductor photodetector and photovoltaic devices. These approaches enable realization of improved power conversion efficiency in quantum-well solar cells, potentially leading to efficiencies in excess of the Shockley-Queisser single-homojunction limit, and to engineer the wavelength response of silicon-based photodetector structures using lithographically patterned metal scattering structures.**

I. INTRODUCTION

The last several years have witnessed an explosion of interest in understanding and exploiting the optical properties of metals and metallic nanostructures, most specifically those associated with plasmonic resonances that can give rise to pronounced optical absorption, field localization, and scattering effects. Applications for which plasmonic phenomena have been or are currently being explored include molecular sensing and tagging, focusing of light, near-field optical microscopy, subwavelength photonics, and optical metamaterials. The appeal of plasmon excitations for such applications typically arises from the large electromagnetic field enhancement that occurs in the vicinity of the metal surface, and the dependence of the plasmon resonance wavelength on nanostructure size, shape, and local dielectric environment, or from very strong scattering effects that occur at wavelengths in the vicinity of plasmonic resonances. Related scattering effects also arise in the presence of dielectric nanostructures. In semiconductor optoelectronic devices, plasmonic phenomena and related effects offer new opportunities to engineer the performance of photodetectors, photovoltaics, and light emitting structures via improved coupling between optical processes in the device active region and incident or emitted light. Here we emphasize application of these effects in photodetectors and photovoltaic devices.

II. PHOTODETECTORS

Optical scattering by nanoparticles or other nanostructures atop a semiconductor photodetector can lead to coupling of photons incident normal to the device surface into optical waveguide modes within appropriately designed semiconductor thin-film device structures, due to the introduction of a lateral wave vector component in the scattered wave. This concept was first demonstrated over a decade ago in studies of photocurrent response in silicon-on-insulator photodetectors on which metallic nanoparticles were synthesized by thin-film deposition on a low-surface-energy dielectric followed by thermal annealing [1].

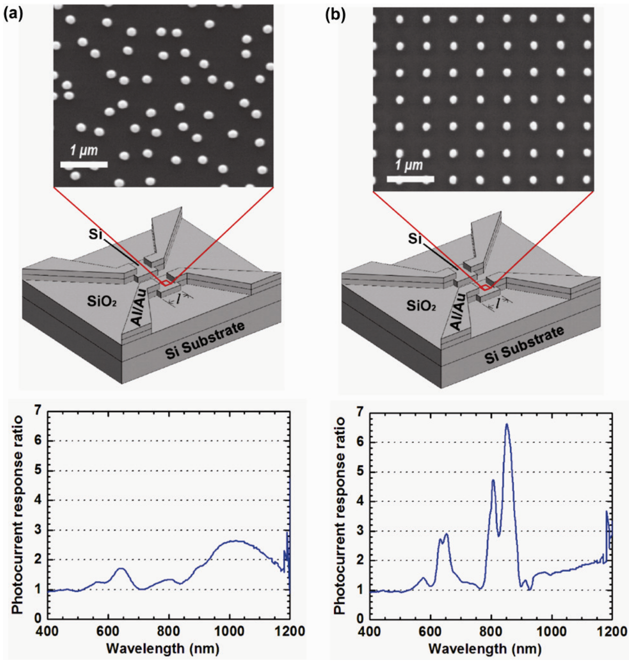

Fig. 1. Au nanostructure arrays fabricated atop silicon-on-insulator photodetector structures and resulting change in photocurrent response, plotted as a ratio of photocurrent with Au nanodot array present to that without nanodot array, for (a) random and (b) periodic nanodot arrays.

The resulting wavelength response of a detector incorporating such effects is determined by the detailed interplay between the optical waveguiding properties of the semiconductor and the scattering behavior of the nanostructures on the surface [2]. For example, periodic arrangements of scattering structures atop the device can enable large enhancements in photocurrent response at specific wavelengths to be attained [3]. Fig. 1 shows Au nanodot arrays fabricated by electron-beam lithography atop silicon-on-insulator photodetectors in either random or periodic spatial arrangements, with the same nanostructure density in both cases. As shown in the figure, the photocurrent response enhancement resulting from scattering by the Au nanodot array changes dramatically upon introduction of periodicity to the

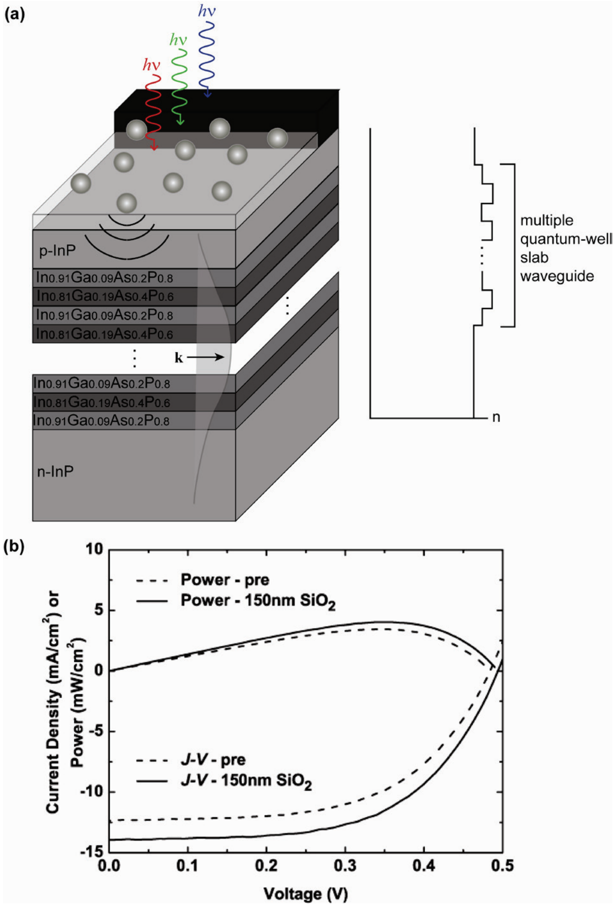

Fig. 2. (a) Schematic diagram of quantum-well solar cell structure, incident illumination geometry, optical waveguide mode induced by elevated refractive index of multiple-quantum-well slab waveguide structure, and nanoparticles on surface for scattering of photons into slab waveguide modes. (b) Current density-voltage and power output curves showing ~13% increase in short-circuit current density and ~17% increase in power conversion efficiency from nanoparticle scattering into multiple-quantum-well slab waveguide modes.

array, with the array periodicity enabling large, wavelength-specific enhancements in photocurrent response to be engineered over a broad range of wavelengths. This approach can then enable, for example, different wavelength response profiles to be realized within a detector imaging array solely through lithographic patterning of structures atop a uniform semiconductor layer structure. In addition, these effects can provide increased flexibility in device design by enabling large increases in detection sensitivity in device layers that ordinarily would be too thin to provide high optical absorption efficiency.

III. PHOTOVOLTAICS

These concepts can also be applied to the engineering of photovoltaic devices. In particular, metal or dielectric nanostructure scattering effects provide increased design flexibility that can enable high optical absorption efficiency to be attained in structures designed for optimum transport behavior of photogenerated carriers, which often can be incompatible with efficient optical absorption. An example of this approach is shown in Fig. 2. Quantum-well solar cells [4] have been explored as potential candidates for high-efficiency photovoltaics, with predicted efficiencies ranging from ~45% [5] to over 60% [6] - well in excess of the Shockley-Queisser limit for single pn homojunction devices of ~31% (under unconcentrated solar illumination). However, the design of quantum-well solar cells with simultaneously high efficiency in both photon absorption and photogenerated carrier collection is highly challenging: typical quantum-well solar cells suffer from a tradeoff between having a sufficient number of quantum wells to ensure high photon absorption efficiency and the resulting reduction in carrier collection efficiency.

As shown in Fig. 2, nanoparticle scattering can be exploited to enable high optical absorption efficiency to be attained in structures with thin multiple-quantum-well regions as required for optimal collection of photogenerated carriers, but which would ordinarily preclude efficient absorption due to insufficient thickness [7]. The elevated refractive index in the multiple-quantum-well region leads to formation of a slab waveguide structure within the device, and scattering of incident photons by metal or dielectric nanoparticles on the device surface enables coupling of normally incident photons into waveguide modes in which photons propagate laterally rather than vertically. This dramatically increases the photon path length within the active device region, even in devices with multiple-quantum-well layers sufficiently thin (~0.2-0.3μm) to enable efficient collection of photogenerated carriers. This approach provides a foundation for development of quantum-well solar cells in which optical absorption and photogenerated carrier collection can be optimized simultaneously, potentially enabling realization of quantum-well solar cells with power conversion efficiencies well in excess of the Shockley-Queisser limit.

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