Nanophotonics for Sustainable Energy

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Abstract

Sustainable energy has become a critical challenge for modern society. Energy efficiency and renewable energy are "twin pillars" of sustainability. In this paper we present applications of nanophotonics in both aspects: (1) Electronic-photonic synergy for Green Information Technology by combining the merits of photons in ultralow energy data transmission with those of electrons in high capacity data processing on a single silicon microchip; (2) Self-assembled nanophotonic structures for light-trapping in thin-film solar cells to improve performance/cost ratio of photovoltaics. Efficiently manipulating radiated electromagnetic energy, nanophotonics will "light up" the future of energy sustainability.

1. Introduction

Energy sustainability has gained global attention in the past decade due to its profound social and environmental impact. Improving energy efficiency of existing systems and performance/cost ratio of renewable energy are two major technical aspects of sustainable energy. In this paper, we present applications of nanophotonics in energy-efficient Green Information Technology (IT) as well as thin-film solar cells (TFSCs) with enhanced performance, addressing both aspects of sustainable energy. In our Information Age, energy consumption of Information Technologies (IT) has become an increasingly prominent concern as the internet traffic doubles every 2 years. It has been estimated that IT already consumes ~ 5% of the total electricity production in the U.S., and it will increase to >10% by 2018 in developed countries [1]. At high bandwidths, data transmission through electrical interconnects can consume even more energy than data processing due to Joule heating and RC delay [2]. Electronic-photonic synergy based on silicon nanophotonics offers a promising solution to Green IT by combining the merits of photons in ultralow energy, high bandwidth data transmission with those of electrons in high capacity data processing on a single microchip [1]. However, monolithic electronic-photonic integration has been hindered by incompatibility in materials and fabrication process. To address this issue, we extend the functionality of Ge-on-Si, which has already been applied to high mobility transistors in silicon nanoelectronics, to integrated active photonic devices by engineering the band structure of Ge using tensile strain and n-type doping. Ge-on-Si ultra-low energy photonic modulators, waveguide-coupled photovoltaic photodetectors and monolithic lasers are demonstrated for large-scale photonic interconnects. In terms of renewable energy, TFSCs have become the fastest growth sector in photovoltaics due to a significant reduction in material consumption and associated costs. However, the performance is traded-off due to insufficient optical absorption in the thin semiconductor films. We designed and fabricated a nanophotonic light-trapping structure using self-assembled, pseudo-periodic porous alumina as a template to enhance optical absorption in TFSCs and improve its energy conversion efficiency. A relative efficiency improvement of 21% has been demonstrated, and it can be further improved to 50% enhancement if the structure can be implemented adjacent to the thin film Si layer. With significant impact on energy technologies such as Green IT, solar cells and solid state lighting, nanophotonics will help to "light up" the future of energy sustainability.

2. Monolithically Integrated Ge-on-Si Active Photonic Devices for Green IT

Active photonic devices, including lasers, modulators and photodetectors, are indispensible components of photonic circuits. Traditionally, they are made of direct gap semiconductors such as III-V materials since the efficient direct gap transition offers excellent optoelectronic properties. However, III-V semiconductors are not compatible with silicon for monolithic integration. Germanium has become an attractive candidate for active photonic devices on Si due to its pseudo direct gap behavior and compatibility with Si electronics. The direct gap of Ge at Γ valley is 0.8 eV, only 136 meV higher than the indirect band gap (Fig. 1a). It corresponds to a wavelength of 1550 nm, the most technically important wavelength in optical communications. The difference between direct and indirect gaps of Ge can be further reduced by introducing tensile strain to enhance its optoelectronic properties, as shown in Fig. 1b. We have incorporated 0.2-0.3% thermally induced tensile strain into epitaxial Ge utilizing the difference in thermal expansion coefficient between Ge and Si, which extends the absorption range of Ge photodetectors from C band (1528-1560 nm) to L-band (1561-1625 nm) [3]. The electroabsorption (EA) contrast in Ge has also been significantly improved by tensile strain [4], which enables

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ultralow energy EA modulators. To obtain efficient light emission from the direct gap transition of Ge, we add n-type doping to tensile-strained Ge in order to fill the states in indirect gap L valleys so that the energy difference between direct and indirect gaps is compensated (Fig. 1c) [5]. Therefore, band-engineering by tensile strain and n-type doping enables high performance Ge active photonic devices on Si.

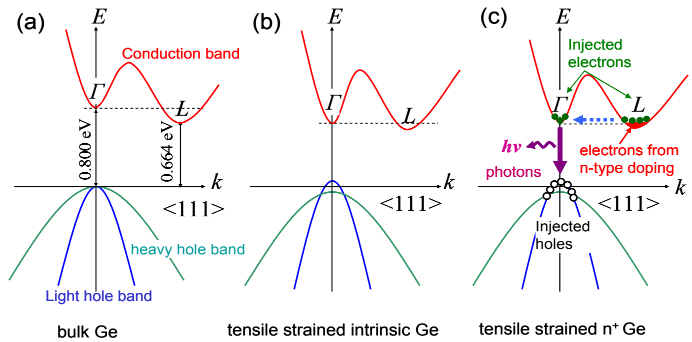

Fig. 1. (a) Schematic band structure of bulk Ge, showing a 136 meV difference between the direct gap and the indirect gap, (b) the difference between the direct and the indirect gaps can be decreased by tensile strain, and (c) the rest of the difference can be compensated by filling electrons into the L valleys by n-type doping.

Photodetectors: Ge-on-Si photodetectors have achieved rapid progress in recent years. Free-space detectors with performance comparable to III-V devices at 850 and 1310 nm have been demonstrated [3]. Integration with high index contrast Si, Si_3N_4 or SiON waveguides enhances bandwidth-efficiency product by separating the photon absorption path in the longitudinal direction (along the waveguide) from carrier collection path in the transverse direction [6]. A bandwidth-efficiency product as high as 30 GHz has been achieved recently in waveguide-coupled Ge photodetectors [7]. Furthermore, we have observed photovoltaic effect in these devices (Fig. 2a), indicating that they can operate at 0 bias with no energy consumption. Alternatively, they can even be applied to recycle scatter laser energy to produce electricity on a photonic chip. Combining the merits of Si in carrier multiplication and Ge in efficient light absorption, Ge/Si avalanche photodiodes have achieved a gain-bandwidth efficiency of 340 GHz, exceeding the performance of their III-V counterparts [8].

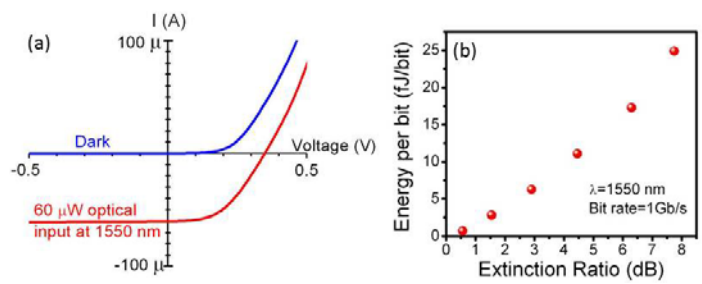

Fig. 2. (a) I-V characteristics of a waveguide-coupled GeSi photodetector with and without laser illumination at 1550 nm. Photovoltaic behavior is clearly demonstrated (b) Energy/bit vs. extinction ratio of a GeSi EAM at 1550 nm. An ultralow energy of 25 fJ/bit is achieved at 8 dB extinction ratio.

Modulators: Ge electroabsorption modulators (EAMs) based on strain-enhanced Franz-Keldysh effect [9] and quantum confined Stark effect (QCSE) [10] have both been demonstrated in recent years. Compared to Mach-Zenhder interferometer modulators based on carrier-injection induced refractive index changes, Ge-based EAMs are based on an ultrafast (<1 ps) and highly efficient field-induced change in absorption near the direct band edge, which enables a very compact device size and ultralow capacitance. These advantages lead to an ultralow energy consumption of 25 fJ/bit (Fig. 2b), which is ideal for highly energy-efficient, large-scale electronic-photonic integration. Compared to low energy silicon ring modulators, GeSi EAMs typically offers a broader operation wavelength range and more tolerance to temperature fluctuations.

Lasers: As discussed earlier, tensile strain and n-type doping can effectively compensate the energy difference between direct and indirect gaps of Ge and achieve direct gap light emission. The performance of an optically pumped, edge-emitting Ge-on-Si waveguide laser is shown in Fig. 3a and b. With the increase of pump power, the spectrum evolved from a broad emission band dominated by spontaneous emission to sharp emission lines featuring stimulated emission [11]. Correspondingly, the polarization evolved from a mixed TE/TM to predominantly TE with a contrast ratio of 10:1 due to the increase of optical gain. A clear threshold behavior is demonstrated in the inset of Fig. 3a. Fig. 3b shows a high resolution scan of the emission line at 1593.6 nm using a spectral resolution of 0.1 nm. Periodic peaks corresponding to longitudinal Fabry-Perot modes are clearly observed in the spectrum. The longitudinal mode spacing of 0.060±0.003 nm is in good agreement with the calculated Fabry-Perot mode spacing of 0.063 nm for a 4.8 mm-long Ge waveguide cavity. These results clearly demonstrate monolithic Ge-on-Si lasers operating at room temperature. As a step towards electrically-pumped Ge-on-Si lasers, we fabricated an edge-emitting n^+ Si/n^+ Ge ($n=1\times10^{19}$ cm^{-3})/p^+ Si waveguide LED by etching a blanket n^+ Ge film on Si. Fig. 3c shows an edge emission spectrum at room temperature from a Ge waveguide LED sample. Clear direct gap electroluminescence was observed in the wavelength range of 1450-1650 nm despite of the significant sidewall roughness due to the reactive ion etching process (RIE). Further increasing n-type doping in Ge is expected to obtain more material gain so that free carrier absorption in the electrodes can be overcome to achieve electrically-pumped lasers.

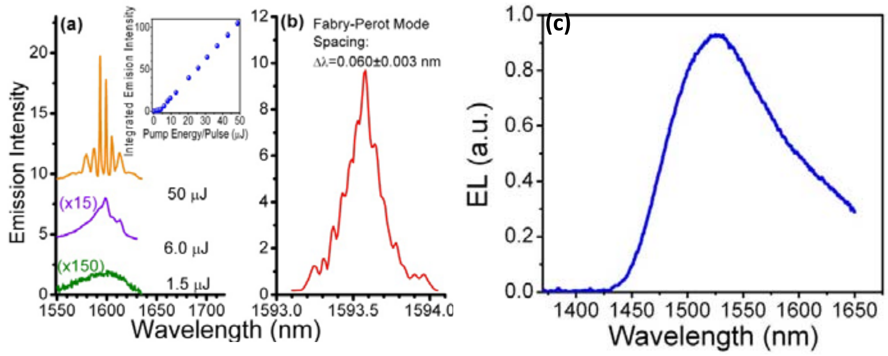

Fig. 3 (a) Edge emission spectra of a Ge waveguide with mirror polished facets under 1064 nm excitation from a Q-switched laser with a pulse duration of 1.5 ns. The three spectra at 1.5, 6.0 and 50 μJ/pulse pumping power correspond to spontaneous emission, threshold for lasing, and laser emission, respectively. (b) High resolution spectrum of the emission peak at 1593 nm under 50 μJ/pulse pumping power. (c) Room temperature electroluminescence spectrum from an edge-emitting Ge-on-Si waveguide LED.

3. Self-Assembled Nanophotonic Structures for Solar Cell Light Trapping

Traditionally, surface texturing has been applied to light trapping in solar cells. In TFSCs, however, textured surfaces increase undesirable surface recombination and induce parasitic loss at the transparent conductive oxide (TCO)/metal interface. Photonic crystals have also been proposed to enhance light trapping [12], but the fabrication typically requires sophisticated lithography which is hard to scale to large area. Here we design and fabricate a backside nanophotonic structure comprising a Si/SiO_2 high-index-contrast diffraction grating and a distributed Bragg Reflector (DBR), utilizing self-assembled porous alumina membrane (PAM) as a template. The grating diffracts incident light into oblique angles to increase the optical path length, while the DBR structure prevents light from leaking out of the back surface (Fig. 4a). According to our optimized design in Fig. 4b, a pseudo-periodic PAM membrane mask layer with a period of ~700 nm and a porosity of nearly 50% was fabricated on top of a thin film microcrystalline silicon (μc-Si) solar cell. The period and pore sizes are controlled by the DC voltage and chemical solution during anodization of Al. Silicon was deposited through the PAM mask to form 2D grating (Fig. 4c) with a thickness of 120 nm. The Si pattern was cover with SiO_2 followed by deposition of Si/SiO_2 DBR pairs to complete the self-assembled nanophotonic structure.

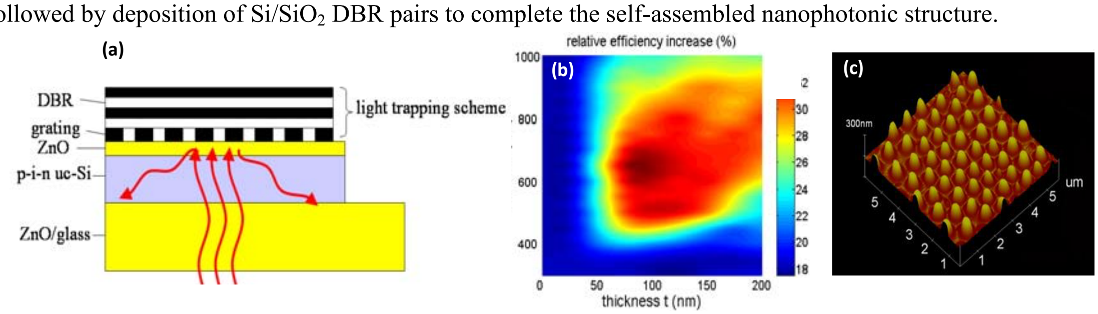

Fig. 4 (a) Schematic structure of the nanophotonic ligh-trapping structure (b) Theoretical modeling of efficiency enhancement vs. grating period and thickness (c) AFM image of pseudo-periodic Si grating fabricated using self-assembled porous alumina membrane as a mask layer.

The photovoltaic performances of solar cells with different back structures were measured under AM1.5G spectrum. Figure 5a a shows the current density (J) – voltage (V) curves. The short-circuit current density and energy conversion efficiency increase by 23% and 21%, respectively, with the backside nanophotonic light trapping structure. The external quantum efficiency spectrum in Fig. 5b confirms that the enhancement is mainly due to increased absorption in the wavelength ragne of 600-850 nm associated with light trapping. Our modeling shows that the enhancement can be further improved to 50% if this nanophtonic structure can be implemented directly adjacent to the semiconductor absorption layer (a-Si in this case).

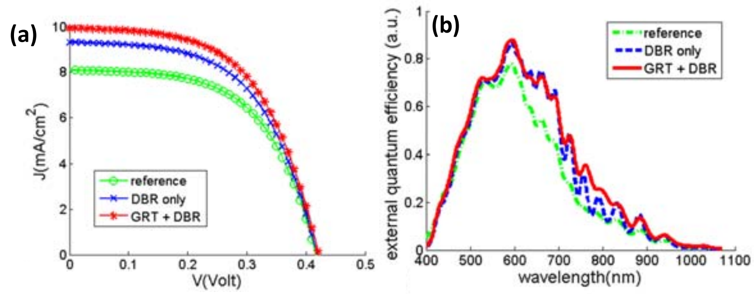

Fig. 5 (a) J-V curves under AM 1.5 G spectrum, and (b) External quantum efficiency spectrum demonstrating efficiency enhancement using nanophotonic light-trapping structures.

4. Conclusion

We have demonstrated applications of nanophotonics in energy-efficient Green IT as well as thin-film solar cells for high performance/cost ratio photovoltaics, addressing both aspects of sustainable energy. With significant impact on energy technologies such as Green IT, solar cells, and solid state lighting, nanophotonics will help to “light up” the future of energy sustainability.

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