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Modeling Techniques for Multijunction Solar Cells

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Abstract—**Multi-junction solar cell efficiencies far exceed those attainable with silicon photovoltaics. Recently, this technology has been applied to photonic power converters with conversion efficiencies higher than 65%. These devices operate well in part because of luminescent coupling that occurs in the multijunction device. We present modeling results to explain how this boosts device efficiencies by approximately 70 mV per junction in GaAs devices. Luminescent coupling also increases efficiency in devices with four more junctions, however, the high cost of materials remains a barrier to their widespread use. Substantial cost reduction could be achieved by replacing the germanium substrate with a less expensive alternative: silicon. Threading dislocations introduced by the lattice mismatch between silicon and other layers have a detrimental effect on performance. In this research, we seek to accommodate lattice mismatch by introducing a voided germanium interface layer on the silicon substrate to intercept dislocations and prevent them from reaching the active layers. We present simulation results exploring the effect of threading dislocations and substrate doping on device performance.**

Keywords— luminescent coupling, transfer matrix method, drift diffusion calculations, voided germanium, multijunction solar cells, concentrator photovoltaics, lattice mismatched substrate, threading dislocations, inorganic semiconductors, modeling

I. Introduction

The highest efficiency solar cells commercially available use multiple lattice-matched junctions to harness as much of the sun's energy as possible. Recently, this technology has been applied to photonic power converters with conversion efficiencies higher than 65%. These devices operate well in part because of luminescent coupling that occurs in the multijunction device [1]. Luminescent coupling also increases efficiency in devices with four more junctions, however, the high cost of materials remains a barrier to their widespread use. These devices, based on III-V semiconductors, are grown on relatively expensive germanium substrates with only a fraction of the substrate being used for energy generation while the remainder serves as a mechanical support. Even under concentration, the system cost is too large to compete with standard silicon photovoltaics for many applications. Various techniques are being explored to reduce the cost of III-V semiconductor technologies by either substrate removal and reuse [2] or replacement of the substrate with a less expensive alternative, such as silicon [3].

When germanium is grown on silicon, the lattice mismatch between the materials (about 4%) causes a high density of defects at the interface [4]. Many of these defects propagate towards the surface, resulting in threading dislocations that inhibit minority carrier collection [3] In this research, we are investigating the use of a voided germanium interface layer to intercept dislocations before they reach the surface, enabling epitaxial growth of high quality Ge, IV (e.g. SiGeSn), and III-V (e.g. InGaAs, InGaP) semiconductors on Si substrates.

By modelling multijunction solar cell designs on Si substrates, we investigate the impact of threading dislocations on device performance. With highly doped Si, we show that it is theoretically possible to achieve device efficiency approaching 30% under 100 sun illumination with dislocation densities approaching 10^6 cm^{-2}, while for low defect densities of 10^4 cm^{-2}, we calculate efficiencies exceeding 35%.

II. Triple-Junction Solar Cell Simulations at 1 Sun

Detailed models of triple-junction solar cells on Si substrates using quasi-monocrystalline Ge interface layers were developed in Synopsys Sentaurus, with the basic geometry shown in Fig. 2.

The impact of doping in the Si substrate and Ge interface doping for 0 threading dislocation density (*TDD*) is shown in Fig. 2. In that case, high efficiency is observed for dopings higher than 10^{18} cm^{-3}. This is more detailed in the short circuit band diagrams show in Fig. 3. By introducing high doping levels in the Si (> 10^{18} cm^{-3}), the height of the potential barrier is reduced so that p-type carriers are able to travel freely.

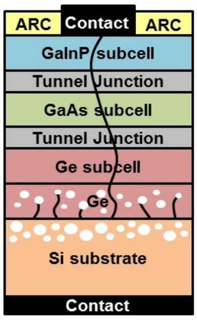

Fig. 1. Schematic of the proposed multijunction solar cell design.

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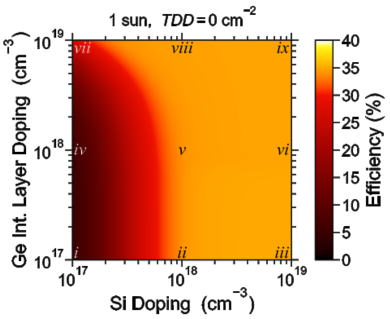

Fig. 2. Triple-junction solar cell efficiency at 1 sun vs. Si substrate and Ge interface layer doping, cell designs indicated.

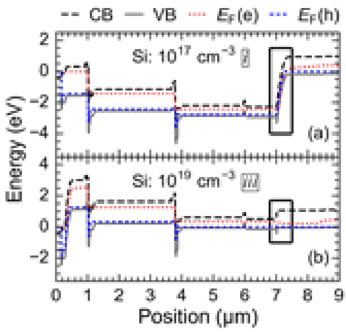

Fig. 3. Short-circuit band diagrams for (a) low and (b) high doping in the Si substrate. Potential barrier at Ge/Si interface is boxed. Ge interface layer doping is 10^{17} cm^{-3}, *TDD* = 0 cm^{-2}.

III. Triple-Junction Solar Cell Simulations under Concentrated Illumination

Under concentration, we observe that the doping of the Si layer must be higher than 6×10^{18} cm^{-3} to obtain the logarithmic increase in efficiency observed in photovoltaics operating under concentration (Fig. 4). Fig. 5 studies the impact of the threading dislocations on minority carrier lifetime according to:

$$\frac{1}{\tau}=\frac{1}{\tau_{\max}}+\frac{\pi^3\cdot TDD}{4} \qquad (1)$$

where *TDD* is the threading dislocation density, τ is the minority carrier lifetime, *D* is the minority carrier diffusion length and $\tau_{\max}$ is the minority carrier lifetime for *TDD* = 0 [5]-[6].

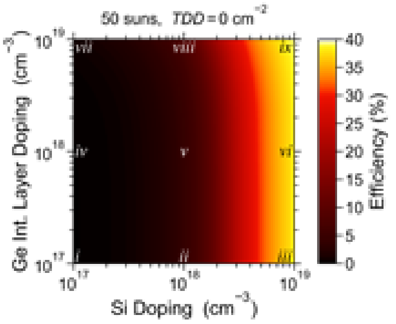

Fig. 4. Triple-junction solar cell efficiency at 50 suns vs. Si substrate and Ge interface layer doping, cell designs indicated.

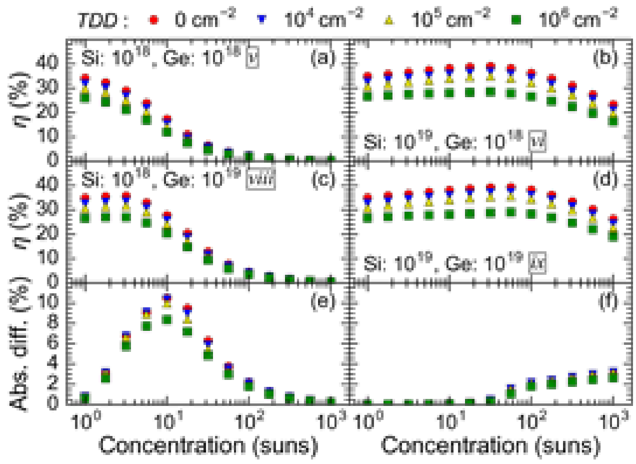

Fig. 5. (a)-(d) Triple-junction solar cell efficiency, η, vs. irradiance. Doping concentrations are indicated. (e), (f) Absolute efficiency gain obtained by increasing Ge interface layer doping from 10^{18} to 10^{19} cm^{-3} for Si doped at (e) 10^{18} and (f) 10^{19} cm^{-3}.

Fig. 5 shows under moderate concentration between 10 and 100 suns with high doping in the Si substrate (10^{19} cm^{-3}) yield theoretical efficiencies exceeding 36% for low threading dislocation densities ($\leq 10^4$ cm^{-2}) and, for higher dislocation densities on the order of 10^6 cm^{-2}, efficiencies approaching 30%.

Acknowledgment

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