The Role of Intervalley Phonons in Hot-Carrier Transfer and Extraction in $InAs/AlAs_{0.16}Sb_{0.84}$ Quantum-Well Solar Cells

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Much of the recent work in hot-carrier solar cells has focused on inhibiting hot-carrier relaxation through the creation of a phonon bottleneck, whereby the reabsorption of LO phonons at high excitation power reduces hot-carrier thermalization rates. We present a different approach in which the band structure of the constituent materials is utilized to store and transfer hot electrons in the upper L and X valleys of InAs quantum-well layers in a superlattice absorber, and then extract the carriers via energy selective n-$Al_{0.35}In_{0.65}As$ and p-$AlAs_{0.16}Sb_{0.84}$ contact layers [1].

The electro-optical properties of p-i-n diodes with an $InAs/AlAs_{0.16}Sb_{0.84}$ superlattice absorber were characterized with simultaneous continuous-wave photoluminescence and monochromatic current density-voltage measurements. The experiments revealed a stable hot-carrier population not only at a relatively low excitation power, but which was nearly independent of excitation power. This behavior is attributed to preferential scattering of high-energy electrons from the Γ valley to the upper metastable satellite valleys of the InAs conduction band, which inhibits carrier thermalization via LO phonon emission. Both a high electric field and optical excitation are shown to enable hot-carrier generation in the InAs quantum wells. However, the extraction of electrons from the absorber to the n-$Al_{0.35}In_{0.65}As$ layer is inhibited by the mismatch in the L to Γ valley degeneracy across the $InAs/Al_{0.35}In_{0.65}As$ interface. A strength of this approach is that hot-carrier extraction is facilitated by well-established physical effects, namely intervalley scattering and the Gunn effect. Luminescence data provide evidence of a stable hot carrier population, which is shown to impact the performance of the device under practical operating conditions without the need for a phonon bottleneck. As such, this approach provides a viable route towards a hot-carrier solar cell.

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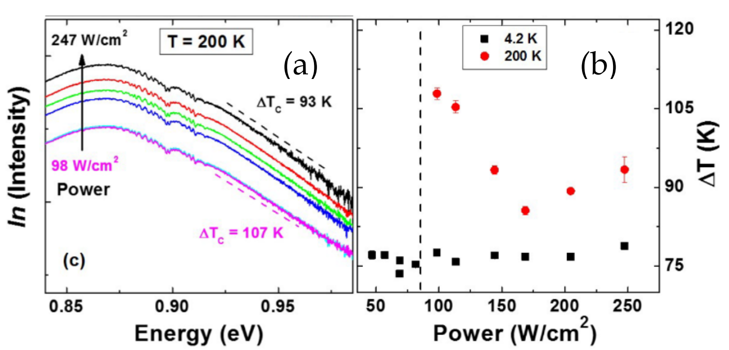

Figure 1. (a) Power dependent photoluminescence at 200K. (b) Carrier temperature minus lattice temperature as a function of excitation power at a lattice temperature of 4.2 K (black) and 200 K (red). [1]

Supplementary Pages

Figure 2 shows the layer structure for the p-i-n photodiode device, which was grown by molecular beam epitaxy. The absorber is a 10-period superlattice with electron wells made of 2.1 nm-thick InAs layers and electron barriers made of 5 nm-thick $AlAs_{0.16}Sb_{0.84}$ layers. Holes and electrons are extracted from the absorber through a p-type $AlAs_{0.16}Sb_{0.84}$ layer and an n-type $Al_{0.35}In_{0.65}As$ layer, respectively.

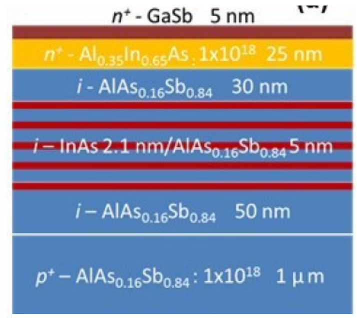

Figure 2. Layer structure for the p-i-n device.

The temperature of the photoexcited electrons can be extracted from fitting a generalized Planck's law to the high-energy tail of the photoluminescence data shown in Figure 1a. The extracted carrier temperature is shown in Figure 1b as a function of excitation power. The data show that the carrier temperature is ~80K and ~300K when the lattice temperature is 4.2K and 200K, respectively. Note that the carrier temperature is insensitive to the excitation power in this low-power regime.

Figure 3a shows a comparison at 300K of the calculated scattering rate for both emission and absorption of polar optical and satellite valley phonons (L, X) for bulk InAs. As the energy of the photoexcited electron is increased, the contribution of intervalley scattering increases and dominates at electron energies of 0.8 eV. Upon photoexcitation at the Γ valley, hot electrons are rapidly scattered to higher-energy L- and X-valleys. They are "stored" in these metastable states because the density of states in these valleys is much larger than for the Γ valley. The efficiency of intervalley scattering aided by an applied electric field is shown in Figure 3b. The calculated occupation probability in the L-valley with respect to the Γ valley is plotted as a function of applied electric field at 300K. At a field greater than 17 kV/cm, the occupation of the L-valley is more probable. The calculations in Figure 3 support the interpretation of the observed hot-carrier effects as due to intervalley scattering of electrons that are hot due to absorption of high-energy photons or acceleration due to a high applied electric field.

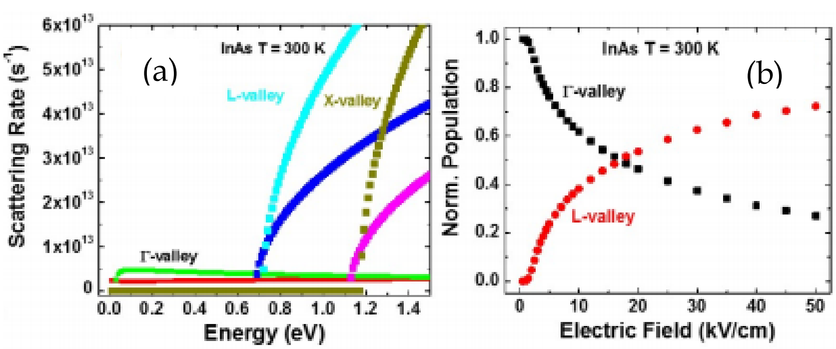

Figure 3. (a) Comparison of the electron scattering rates as a function of energy (for both emission: green, cyan, saffron and absorption: red, blue, magenta) for polar optical phonons and intervalley phonons in InAs at 300 K. (b) Occupation probability in the Γ- and L-valleys as a function of electric field in InAs at 300 K. [1]