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Minority-carrier mobility enhancement in p^+ InGaAs lattice matched to InP

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Minority electron mobilities in p^+-In$_{0.53}$Ga$_{0.47}$As have been measured with the zero field time-of-flight technique. The room-temperature (297 K) minority electron mobilities for p^+-In$_{0.53}$Ga$_{0.47}$As doped 0.9 and 3.1×10^{19} cm^{-3} are found to be 2900 and 3300 cm^2 V^{-1} s^{-1}, respectively. These are the first measurements to demonstrate enhancement in minority-carrier mobility as doping is increased for heavily doped In$_{0.53}$Ga$_{0.47}$As. This enhancement in mobility as doping is increased is similar to that observed in p^+-GaAs, which has been attributed to reductions in plasmon and carrier–carrier scattering between minority electrons and majority holes.

In$_{0.53}$Ga$_{0.47}$As has emerged as a very important material for use in heterojunction bipolar transistor (HBT) structures lattice matched to InP substrates. In$_{0.53}$Ga$_{0.47}$As has a number of properties that make it a good choice for HBTs: it has an extremely small electron effective mass and a very large separation between the Γ and L valleys in the conduction band that can allow for higher velocity overshoot.[1] To accurately design and analyze InGaAs based heterojunction bipolar transistors (HBTs), it is important to understand the minority-carrier transport properties of heavily doped p-In$_{0.53}$Ga$_{0.47}$As. Here, we present the first measurements of an enhancement in minority-carrier mobility for increasing doping in In$_{0.53}$Ga$_{0.47}$As.

The photodiode films used for this study were grown by the metalorganic molecular-beam epitaxy (MOMBE) technique. Arsine and phosphine served as group V sources, trimethylindium and triethylgallium as the group III sources, and thermal beams of Be and Sn derived from elemental sources as p- and n-type dopants, respectively. The growth apparatus and procedures were previously described.[2,3] The films consisted of an InP buffer layer grown on the InP substrate, a thin n-In$_{0.53}$Ga$_{0.47}$As base region, and a thick p-In$_{0.53}$Ga$_{0.47}$As emitter region. A thin InP window was grown on top of the emitter region to insure that the surface recombination velocity at the heterointerface was less than 10^4 cm/s, and a thin In$_{0.53}$Ga$_{0.47}$As cap was placed on top of the window to facilitate ohmic contact formation (see Fig. 1). The 500 $\times$ 500 μm^2 diode mesas were wet etched using 4:1:10 H$_3$PO$_4$:H$_2$O$_2$:H$_2$O to selectively etch In$_{0.53}$Ga$_{0.47}$As and 3:1 H$_3$PO$_4$:HCl to selectively etch the InP window region. The thickness of the InGaAs region was measured with an Alpha Step profilometer. Ohmic contact to the emitter region was made with Au:Ti:Au metalization shadowing less than 2% of the diode mesa, and the device was mounted in a high-speed package to minimize circuit effects.

The zero field time-of-flight[4] (ZFTOF) technique was used to measure the minority electron diffusivity D_n. In this technique, the photodiodes described above are photoexcited with <0.5 ps full width at half-maximum (FWHM) pulses from a Coherent Mira 900f Ti:sapphire laser pumped with 14 W from a Coherent Innova 415 argon-ion laser. A Conoptics Pockels cell is used to reduce the laser repetition rate to $\sim$5 kHz in order to allow sufficient time for the transient response to decay before the next pump pulse arrives. Excitation wavelengths of both 720 and 440 nm were used in this study, where 440 nm was obtained by doubling the Ti:sapphire output at 880 nm using a 2-mm-thick β-BaB$_2$O$_4$ (BBO) crystal. The optical pulse generates electron hole pairs near the top surface of the emitter region of the photodiode. The electrons then diffuse in a zero-field environment to the edge of the depletion region and are collected by the junction. To extract D_n, the measured transient response is fit to a one-dimensional numerical simulation of transport in the p-In$_{0.53}$Ga$_{0.47}$As emitter region with fitting parameters being diffusivity (D_n), lifetime, and surface recombination velocity (S_f) at the top InP/InGaAs interface. The use of InP as a passivation layer for the InGaAs region ensures that $S_f < 10^4$ cm/s, which minimizes the effect of S_f on the transient response. The ZFTOF transient responses for the InGaAs structures studied here are sensitive to both the

FIG. 1. ZFTOF diode structures used for mobility measurements. N^* is the emitter doping density and W^* is the emitter width. For $N^* = 0.9 \times 10^{19}$ cm^{-3}, $W^* = 2.2$ μm and for $N^* = 3.1 \times 10^{19}$ cm^{-3}, $W^* = 1.7$ μm.

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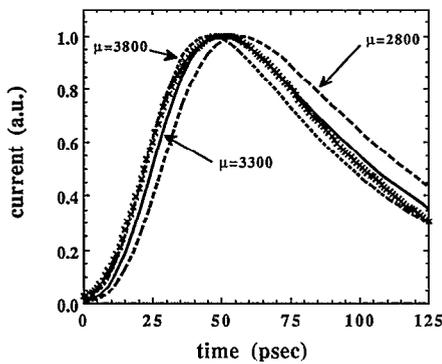[b] Present address: Technion Institute, Haifa, Israel.

FIG. 2. Example 297 K ZFTOF response for a p-InGaAs photodiode doped 3.1×10^{19} cm^{-3} with an excitation wavelength of 440 nm. Included in this plot are numerical simulation results with mobility=3300 cm^2 V^{-1} s^{-1} and lifetime=0.1 ns. Also included are simulations with $\pm 15\%$ change in mobility.

minority electron lifetime and diffusivity. The minority electron mobility is obtained from the diffusivity with the Einstein relation. An example of the measured and simulated ZFTOF response for the InGaAs sample doped 3.1 $\times 10^{19}$ cm^{-3} is presented in Fig. 2.

Steady-state measurements of the internal quantum efficiency (IQE) versus wavelength of the diode structure were also performed to give independent information about the diffusion length under the assumption of low S_f.[5] Accurate modeling of the IQE requires accurate knowledge of the absorption coefficient of InGaAs; unfortunately, the reported absorption coefficients for InGaAs vary by as much as 50%.[6,7] For the InGaAs photodiodes used in this study, the IQE is very sensitive to the diffusion length as shown in Fig. 3. Including the uncertainty in the absorption coefficient, we estimate the accuracy of the diffusion length determination by IQE to be $\pm 20\%$.

Combining both the IQE results and the ZFTOF results, we obtain room-temperature (297 K) minority electron mobilities of 2900 and 3300 cm^2 V^{-1} s^{-1} for the hole concentrations of 0.9 and 3.1×10^{19} cm^{-3}, respectively, using an excitation wavelength of 440 nm. For excitation at 720 nm, we obtain approximately 6% lower mobilities. For both ZFTOF excitation wavelengths we obtain effective
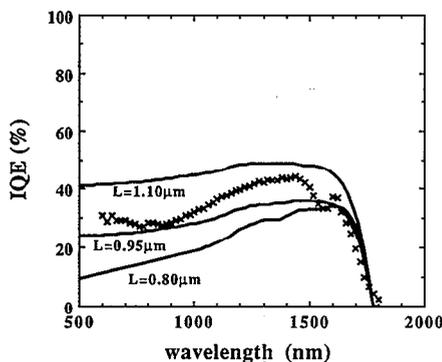

FIG. 3. Internal quantum efficiency (IQE) measurements for the In-GaAs ZFTOF diode doped 3.1×10^{19} cm^{-3}. The solid lines are theoretical IQE results for the diffusion lengths (L) of 0.80, 0.95, and 1.10 μm, assuming the front surface recombination velocity is low ($< 10^4$ cm/s).

lifetimes of 0.3 and 0.1 ns for doping densities of 0.9 and 3.1×10^{19} cm^{-3}, respectively. The small discrepancy between the 720 and 440 nm results may be attributed to uncertainties in the absorption coefficient at 720 nm and systematic experimental error in the time zero determination.

There are three major sources of errors that can result in uncertainties in the mobility measurements. First, uncertainties in the lifetime may cause significant error in the measured mobility. The 20% uncertainty in the IQE measurement of the diffusion length, when combined with the ZFTOF measurements, results in less than 15% uncertainty in mobility due to ~30% error in lifetime estimation. Second, photon recycling[8] where additional electron-hole pairs are generated throughout the device due to the absorption of photons emitted during radiative recombination events may also be significant for these samples. Numerical simulations[4] of photon recycling in the structures used in this study indicate that the effect of photon recycling on the measured mobility is minimal, while the effect on lifetime may be as large as a factor of 2. Thus the lifetimes presented here should be viewed as effective lifetimes that have been enhanced by photon recycling. The final source of error results from the assumption that the carrier transport is entirely diffusive. The carriers are generated with about 1.0 and 2.0 eV excess energy for 720 and 440 nm excitation, respectively. If these "hot" carriers do not thermalize quickly then the assumption of entirely diffusive transport would not be valid. Femtosecond carrier relaxation measurements in p^+-GaAs (Refs. 9 and 10) show that electrons rapidly thermalize in < 0.5 ps and decay to the lattice temperature with an ~ 1 ps time constant. Similar results appear to hold for $In_{0.53}Ga_{0.47}As$.[11] Thus we do not expect the large excess energy of the electrons to have a significant effect on the measured mobility.

As a comparison, the measured mobilities in p^+-$In_{0.53}Ga_{0.47}As$ are about 2.1 and 1.2 times larger than the measured mobilities in p^+-GaAs,[12,13] which may most likely be attributed to the smaller electron mass in $In_{0.53}Ga_{0.47}As$. These results also indicate that, like p^+-GaAs, p^+-$In_{0.53}Ga_{0.47}As$ shows an enhancement in minority electron mobility as doping density is increased for degenerately doped material.[12,13] Lowney and Bennett[14] theoretically demonstrate that a rise in minority electron mobility in p^+-GaAs would be expected as plasmon and carrier-carrier scattering between minority electrons and majority holes are reduced at high hole concentrations. Plasmon scattering is reduced because the hole plasmon frequency becomes too high for interaction with the electrons, and carrier-carrier scattering is suppressed because degeneracy reduces the number of states available to receive a scattered hole.

In conclusion, we have measured minority electron mobilities in p^+-$In_{0.53}Ga_{0.47}As$ of 2900 and 3300 cm^2 V^{-1} s^{-1} for hole concentrations of 0.9 and 3.1×10^{19} cm^{-3}, respectively. These are the first measurements of minority electron mobility in heavily doped $In_{0.53}Ga_{0.47}As$ that demonstrate an enhancement in the minority electron mobility for increasing doping. These results indicate that

the transport of electrons across the base of an InGaAs HBT may be thermally limited. The diffusion velocity ($2D$/base width) for a 500-Å-wide base doped $\sim 3 \times 10^{19}$ cm^{-3} would be 3.4×10^7 cm/s, which is considerably larger than the thermal velocity of electrons in InGaAs.

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