Ion-implanted In 0.53 Ga 0.47 As for ultrafast optoelectronic applications

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Low-temperature (LT) grown and ion-implanted GaAs have been shown to exhibit the properties ideal for ultrafast optoelectronic applications, with good carrier mobilities, high resistivities, and subpicosecond optical response times.1,2 In this material, ionized As antisite defects act as the main electron traps and recombination centers.3 InGaAs lattice matched to InP has an added interest from the point of view of optical fiber communications technology because of its large absorption at the 1.3- and 1.55-μm wavelengths. However, As antisites in InGaAs create shallow donors and, together with other intrinsic defects such as an As vacancy and a group-III (In or Ga) interstitial, prevents fabrication of highly resistive InGaAs layers by LT growth.4 Besides, in LT InGaAs, arsenic antisites appear in lower concentrations than in LT GaAs, therefore, subpicosecond electron lifetimes are not reached.5,6 An electron lifetime of 400 fs was only observed in conductive LT InGaAs grown on a semi-insulating substrate, and a GaAs proximity cap was used on the InGaAs epilayer. According to Transport of Ions in Matter (TRIM) simulations, the ion energy chosen for this work leads an ion range and peak damage depth of ~1 μm. Hall-effect measurements were carried out using the van der Pauw geometry, with sintered indium ohmic contacts.

Carrier dynamics in the implanted InGaAs layers was studied by time-resolved photoluminescence (TRPL) and transient reflectivity (TR). TRPL measurements were performed using an upconversion setup with excitation at 800 nm and PL detection at the band-gap wavelength. Degenerate TR experiments were conducted with a central pump and probe wavelength of 1600 nm. A femtosecond Ti:sapphire laser and an optical parametric oscillator providing pulses of 80–150 fs duration were used in the TRPL and TR experiments, respectively. The photoexcited carrier density and temporal resolution in both experiments was ~1 × 1018 cm−3 and 150 fs, respectively. In the TR experiment, the probe intensity was 0.01 of the pump intensity.

Figure 1 shows the effective mobility μeff and sheet resistance R∥ for 2-MeV Fe2+ implanted InGaAs epilayers at room temperature as a function of annealing for samples implanted to doses of 1 × 1015 and 1 × 1016 cm−2. For the 1 × 1015 cm−2 implantation, μeff is low because conductivity is most probably dominated by the hopping mechanism, which is typical for as-implanted layers. With increased annealing temperature, the mobility increases as the conductivity mechanism changes to band conduction and the concentration of defects decreases. At a 700 °C anneal temperature, the effective mobility is almost 103 cm2 V−1 s−1. The sudden decrease in μeff for annealing at 800 °C can be explained by the activation of deep Fe-related traps acting as efficient scattering centers. The sheet carrier concentration was found to have values on the order of 1011 cm−2 for all annealing temperatures. The as-implanted sheet resistance is fairly low despite the low values of carrier concentration and effective mobility, which is due to the hopping conduction mechanism. Annealing at 500 °C reduces the number of defects...
such that hopping conduction is significantly reduced and the sheet resistance is increased to $\sim 4 \times 10^5 \Omega$/square. Annealing at 600 °C corresponds to the onset of activation of the shallow donor levels, and the increase in $R_s$ for annealing at temperatures above this is attributed to the activation of ever-greater concentrations of Fe acceptors due to more Fe atoms taking up group-III lattice sites.11

The evolution of $R_s$ for $1 \times 10^{16}$ cm$^{-2}$ dose with annealing temperature is essentially similar to that for implantation at the lower dose. The lower mobilities in this case may be due to higher residual damage in these samples. The evolution of the $\mu_{\text{eff}}$ is also consistent with this picture, with a maximum (albeit a small one when compared to the values for $1 \times 10^{15}$ cm$^{-2}$ implantation) for 600 °C annealing. It is worth mentioning that, contrary to Fe-implanted InP,12 implanted InGaAs experiences no type change and remains $n$-type for all annealing temperatures used in this study.

Unimplanted, undoped InGaAs grown by MOCVD is typically $n$-type with $10^{14}$–$10^{16}$ cm$^{-3}$ inadvertent donors.13 The standard practice to achieve highly resistive InGaAs is to compensate these donors with deep acceptors such as Fe or Cr, however, the highest attainable room-temperature resistivity is only on the order of thousands of $\Omega$ cm due to the small band gap and high intrinsic carrier concentration ($n_i \sim 9 \times 10^{11}$ cm$^{-3}$ at room temperature). Consequently, the values of $R_s$, achieved here are at the upper limit of what is achievable for undoped InGaAs.

Defects, affecting the electrical and optical properties of implanted samples, have two sources: complexes resulting from Fe incorporation and native defects caused by disorder within the lattice itself. The low resistivity of ion-implanted and LT-InGaAs has been documented, and is attributed to the existence of donor levels with the activation energy of 30–40 meV.4 After annealing at 600 °C, the antisites have been observed to form precipitates which, being small and widely spaced, were considered to act as slow recombination centers.14 In addition to the native defects, incorporation of Fe atoms into cation sites in InGaAs results in a deep acceptor with an energy of $\sim 0.35$ eV which shifts the Fermi level towards the midgap and increases the resistivity.13 Additionally, it has been found that annealing at high temperatures (e.g., 800 °C) for a relatively short time (e.g., 5 s) results in a large surface buildup of Fe, which increases with annealing time and temperature.11 Therefore, layers with different optical and electrical properties may exist in InGaAs samples prepared under such conditions.

Time-resolved optical measurements were performed only on samples implanted at the $1 \times 10^{15}$ cm$^{-2}$ dose, since these samples have shown larger mobility and rather high resistivity, particularly when annealed at 500 °C. Figure 2(a) shows TRPL transients. The PL magnitude is proportional to the product of the free electrons and holes at the band edges, and the PL decay gives the most direct picture of carrier trapping. The undoped InGaAs sample measured under the same conditions has a rather long PL decay time of 120 ps, which is determined by Auger recombination. The short PL decay times in implanted samples reflect carrier trapping into deep centers. The PL decay times, equal to 1.3, 2.2, 4.0, and 4.5 ps for the implanted samples annealed at 500 to 800 °C, were determined by fitting the PL transients. During the fits, prolonged carrier relaxation, manifesting itself in the long PL rise time for the unimplanted sample [inset to Fig. 2(a)], was taken into account. A drawback in our TRPL measurements is the high excitation energy, compared to that of the band gap. This establishes long times for electron relaxation to the bottom of the band, which, in turn, results in long PL rise times and prolonged PL decay times. In a previous study on LT GaAs, we have shown that for ultrashort electron lifetimes, the process of electron scattering to the bottom of the
band affects the PL transient, and the PL decay becomes considerably longer than the electron trapping time.\textsuperscript{15} The situation in InGaAs for the 800-nm excitation is even more severe: electron scattering to and from the L valley further delays the relaxation.\textsuperscript{16}

In an attempt to avoid the relaxation phenomena and determine real electron trapping times, the TR measurements at the band-gap wavelength have been performed [Fig. 2(b)]. To evade coherent artifact effects, pump and probe pulses had orthogonal polarizations; however, some coherent oscillations still distort the rising part of the curve for the 500 °C sample.

Interpretation of TR transients is much more complicated than that of TRPL because the reflectivity is sensitive to changes both in the absorption coefficient and refractive index. In addition, TR measurements are sensitive not only to the bleaching effect induced by the band-to-band absorption, but also to changes in carrier concentration on impurities, free carrier absorption, etc. However, studies on LT GaAs have shown that the initial fast decay of TR transients is determined mainly by the carrier trapping.\textsuperscript{17,18} Indeed, the TR dynamics for the implanted InGaAs samples annealed at 500 and 600 °C show a single peak, which, after a fit to a function suggested by Roux et al.,\textsuperscript{17} provides electron trapping times of 300 fs. For the 500 °C sample, the trapping time might be even shorter, but is obscured by the temporal resolution of the experiment.

In the 600 °C sample curve, a longer tail with a characteristic time of about 3.5 ps appears, which can be attributed to changes in absorption from the midgap traps.\textsuperscript{18,19} According to the model, trapping of one carrier type to the midgap centers occurs with a characteristic time of 300 fs, and subsequent recombination by the trapping of the other carrier type occurs at the slower rate of 3.5 ps. For the 700 and 800 °C annealed samples, the TR transients are more complicated. Here, we see three different changes in reflection. The initial fast decrease persists for a time at least on the order of 100 ps. A possible explanation for this long-term component consistent with the electrical measurement data could be electron excitation from the deep Fe-related centers, which are expected to be present in samples annealed at higher temperatures at larger densities, and subsequent trapping to the shallow donors. At these donor sites, the carriers can stay for a long time before thermal re-emission into the conduction band and subsequent recombination. On top of this long transient, band-to-band carrier excitation, trapping and recombination manifest themselves through the positive peak in the TR transient. Decay times for these peaks have similar characteristic times to that of TRPL.

Summarizing, similar to Fe-implanted InP,\textsuperscript{12} the shortest carrier lifetimes times in InGaAs are achieved at annealing temperatures much lower than those that have been associated with Fe activation. A jump in sheet resistance occurs for samples implanted at room temperature to a dose of $1 \times 10^{13}$ cm$^{-2}$ when annealed at 500 °C, to a value of $4 \times 10^{12}$ Ω/square, where shallow donor activation has not yet become dominant. Around this annealing temperature, the carrier lifetime is also record-short, at most 300 fs, indicating that these implantation conditions deliver InGaAs layers with characteristics appropriate for ultrafast optoelectronic applications.

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