Order-of-magnitude reduction of carrier lifetimes in [100] n-type GaAs shock-compressed to 4 GPa

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(Received 6 January 2011; accepted 7 February 2011; published online 1 March 2011)

Dynamics of excess carriers, following a short excitation pulse, were recorded in shock-compressed [100] GaAs:Te to 4 GPa using time- and spectral-resolved photoluminescence (PL) measurements. PL signals extending over five orders of magnitude and comprising several recombination mechanisms were detected in single-event experiments. In marked contrast to earlier hydrostatic pressure results, a linear lifetime reduction was observed under uniaxial strain. The present results suggest that the lifetime reaches a minimum at the direct-to-indirect transition. © 2011 American Institute of Physics. [doi:10.1063/1.3561019]

The recombination lifetime of excess carriers is among the most important properties governing the operating characteristics of semiconductor devices. However, carrier lifetime is also the most elusive parameter in device engineering, because it can vary by orders of magnitude depending on material quality, doping concentration, current density, and temperature. Among other factors, strain plays a key role in recombination processes because it perturbs the local electronic structure, thereby introducing alternative recombination paths. Strains to 1%, due to lattice mismatch at different epitaxial interfaces, alter significantly the operation of multilayered devices such as laser diodes and solar cells. Strains as large as 7% are present at the surfaces of quantum dots.

The effects of volumetric strains on recombination processes in doped GaAs samples have been examined using hydrostatic pressure. An increase in nonradiative lifetimes was observed in all samples at 4 GPa, due to the direct-to-indirect band gap transition (DIT). Below 4 GPa, results were dependent on the doping type and the structure studied. A gradual increase in lifetimes was found in p-type GaAs (Ref. 4) and doped double heterostructures while an abrupt decrease in lifetimes at ~2 GPa was detected in n-type GaAs. The latter results for Te-doped GaAs, reproduced by the circle symbols in Fig. 1, were interpreted as the formation of additional recombination centers in GaAs at high strains.

Shear strain, not present under hydrostatic loading, reduces the crystal symmetry and introduces an orientation-dependent splitting and shifting in electronic states. The effects of shear strains were studied in n-type GaAs under [100] uniaxial stress up to 0.5 GPa. The results, reproduced by the square symbols in Fig. 1, were attributed exclusively to changes in transition matrix elements in GaAs. However, the lifetime behavior at higher shear strains has not been observed, due to the intrinsic failure of semiconductor single crystals at larger uniaxial stresses.

Large uniaxial strains in semiconductors can be achieved using shock wave compression. In these experiments, longitudinal stresses are produced along desired crystal orientations by impacting them with accelerated projectiles. In GaAs, longitudinal stresses up to 5.5 GPa (3.5% uniaxial strain) were applied along different crystallographic orientations to demonstrate the anisotropy of DIT thresholds. In the present work, carrier lifetimes were measured in n-type GaAs at various longitudinal stresses along the [100] orientation up to the DIT threshold.

The experimental configuration used in this work has been described previously. The inset of Fig. 2 shows a measured longitudinal stress profile at an optically probed GaAs surface, due to an impact generated compression wave. In this work, time-dependent photoluminescence (PL) signals, following a short 200 ps excitation pulse from a 532 nm laser, were recorded during a state of uniaxial strain (or constant longitudinal stress). The temporal window of the time-resolved PL measurements is indicated by the arrow in the inset of Fig. 2. Recombination dynamics of excess carriers were observed for five different longitudinal stresses up to the abrupt PL signal loss due to the DIT at 3.8 GPa in shock compressed [100] GaAs. Each experiment was performed on a sample cut from the same GaAs wafer with Te doping.

FIG. 1. (Color online) Literature results of lifetime changes in n-GaAs under hydrostatic pressure (circle symbols) and uniaxial stress (square symbols). The vertical scale shows the ratio between the compressed $\tau_{\text{comp}}$ and the ambient $\tau_{\text{amb}}$ lifetimes. Dashed lines are shown for eye guidance.

\[ \text{Uniaxial stress (GPa)} \]

\[ \frac{\tau_{\text{comp}}}{\tau_{\text{amb}}} \]

\[ \text{Pressure (GPa)} \]

\[ \text{DIT} \]

\[ \text{0.0} \]

\[ \text{1.2} \]
of $7 \times 10^{16}$ cm$^{-3}$. All samples were cooled to near liquid nitrogen temperatures during the experiment.

Figure 2 shows a typical example of the PL data (intensity versus wavelength versus time) recorded by a spectrometer, a streak camera and a charge-coupled device detector. At ambient conditions, the arrival of the excitation pulse at 0 ns creates the PL spectrum, which consists of a main peak around 830 nm with a lower wavelength tail. The tail arises from the hot electron-hole plasma generated during the excitation pulse and quickly disappears due to intraband relaxation processes.\textsuperscript{13} The decay of the main PL peak, due to carrier recombination at band-gap energies, continues over a period of $\sim$60 ns. In the 2.7 GPa compression experiment, the PL spectrum has a similar shape but is blueshifted to 770 nm. The peak decay is much faster, indicating clear changes in the recombination rates. The spectral shifts in the main PL peaks at different longitudinal stresses were consistent with the band-gap changes previously reported in shock-compressed [100] GaAs using continuous PL measurements.\textsuperscript{13}

Time-dependent decays of the spectrally integrated peaks, the focus of this work, are shown using a semilogarithmic plot in Fig. 3. The decay at ambient conditions represents an average of multiple data while the decays in shock-compressed states were measured in single event experiments. The shock-compressed data were smoothed by applying an adjacent 30 point averaging algorithm. The PL signals extend over almost five orders of magnitude and show faster recombination with increasing longitudinal stress under uniaxial strain.

Several nonradiative mechanisms govern the ambient decays in doped GaAs. The initial nonexponential part (indicated by $\tau_{\text{init}}$) occurs due to the fast rates of bimolecular and surface recombination.\textsuperscript{16} During shock compression, $\tau_{\text{init}}$ is not affected significantly. The subsequent two-component part with exponential slopes (indicated by the dashed lines) is characteristic of Shockley–Read–Hall recombination at deep-level defects.\textsuperscript{16} The two slopes (Fig. 3) originate from different recombination rates at different carrier concentrations and they are labeled as the saturation lifetime $\tau_{\text{sat}}$ and the minority-carrier lifetime $\tau_{\text{min}}$, respectively. The significant reduction in the well-resolved $\tau_{\text{sat}}$ and $\tau_{\text{min}}$ lifetimes, as a function of stress, is shown in Fig. 4 by the circle and square symbols, respectively. Similar to Fig. 1, the vertical scale shows the ratio between the compressed ($\tau_{\text{comp}}$) and the ambient ($\tau_{\text{amb}}$) lifetimes.

Both $\tau_{\text{sat}}$ and $\tau_{\text{min}}$ lifetimes showed the same linear lifetime decrease with increasing longitudinal stress, as shown by the dashed line in Fig. 4. These findings are in marked contrast to the abrupt lifetime changes inferred under hydrostatic pressure (Fig. 1) and call into question the proposed formation of additional recombination centers at high strains.\textsuperscript{7,8} A linear lifetime decrease under uniaxial stress (Fig. 1), similar to our results, was attributed to changes in transition matrix elements in GaAs. While it is possible that the same intrinsic property dominates in shock compressed GaAs, it is intriguing that the detected lifetime decrease correlates so well with the DIT at 3.8 GPa, as seen from the intercept with the longitudinal stress scale. Experiments on

![FIG. 2.](image1)  
![FIG. 3.](image2)  
![FIG. 4.](image3)
samples having different doping and different orientations, along with a comprehensive lifetime model, are needed to address these issues.

In conclusion, time- and spectral-resolved PL measurements were obtained in [100] GaAs:Te subjected to shock wave uniaxial strain compression. A linear order-of-magnitude lifetime reduction was observed up to the DIT. This behavior is not consistent with the proposed formation of additional recombination centers in highly strained GaAs.7,8

This work was supported by DOE Grant No. DE-FG03-97SF21388.