Electronic Compensation and Ultrafast Carrier Lifetimes in Low Temperature Grown Be-doped InGaAs

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The electronic and optical properties of low temperature grown (LTG), nominally lattice-matched, InGaAs on InP are reported. High optical quality epitaxial InGaAs with a prescribed resistivity and carrier lifetime is highly desirable for ultrafast device applications. Although LTG-GaAs is an established technique for producing these desirable qualities, the narrow gap InGaAs results in heavily n-type material which does not become semi-insulating upon anneal in contrast to GaAs.

Low-temperature InGaAs:Be growth was characterized via a designed experiment in which As-pressure, growth temperature, Be-doping and post-growth anneal conditions were varied. In all, 54 distinct growth/anneal conditions were examined. Growth was performed on epi-ready InP(100) substrates, Indium mounted to Molybdenum blocks, in an all solid source Riber 2300 MBE system. The growth rate for all layers was 1.0 μm per hour performed under an As_4 beam equivalent pressure of either 15 or 30 μTorr. Be cell temperatures of 865, 840 and 780°C were used in this experiment which nominally produce p-type doping levels in InGaAs of 1.0×10^{19}, 2.5×10^{18} and 3×10^{17} cm^{-3}, respectively.

The nature of the electronic defects and the subsequent effects on the electronic and optical properties were characterized by multiple techniques. The picosecond capture dynamics of the impurity levels associated with the deep donor levels were characterized by direct observation of the electron lifetime via time-resolved terahertz spectroscopy. Structural properties were investigated via X-ray diffraction. Temperature-dependent Hall and linear bandedge absorption spectroscopy was also performed. To understand the carrier lifetime and mobility our data was used to train back-propagation neural networks. Using the neural process models, the effect of growth conditions on material properties can be visualized using 3-D contour plots.

We found a complex relationship between the carrier lifetime and the growth conditions. We confirmed, for all growth conditions investigated, that Be-doping shortens the carrier lifetime and maintains the LTG-induced carrier lifetime reduction following anneal in contrast to undoped LTG material. Importantly, the carrier lifetimes were systematically longer for the material grown at the increased As-pressure of 30 μTorr. The effects of increased Be-doping and higher As-pressure were smaller on materials annealed at 600°C as compared to the as-grown and 500°C annealed material. The results of the Hall measurements revealed that LTG-InGaAs:Be was primarily p-type. For a given Be-doping and As-pressure, the material was most strongly p-type at the intermediate growth temperature 350°C. N-type material was produced only at the lowest growth temperature 225°C. The dominant growth condition affecting carrier concentrations and lifetime was the growth temperature. We explain the behavior of the Be doping in terms of a compensation effect, however, some observations suggest the need for additional mechanisms. For example, the Be related defect may act in the form of a Be-As complex and/or may prevent precipitates from being formed.

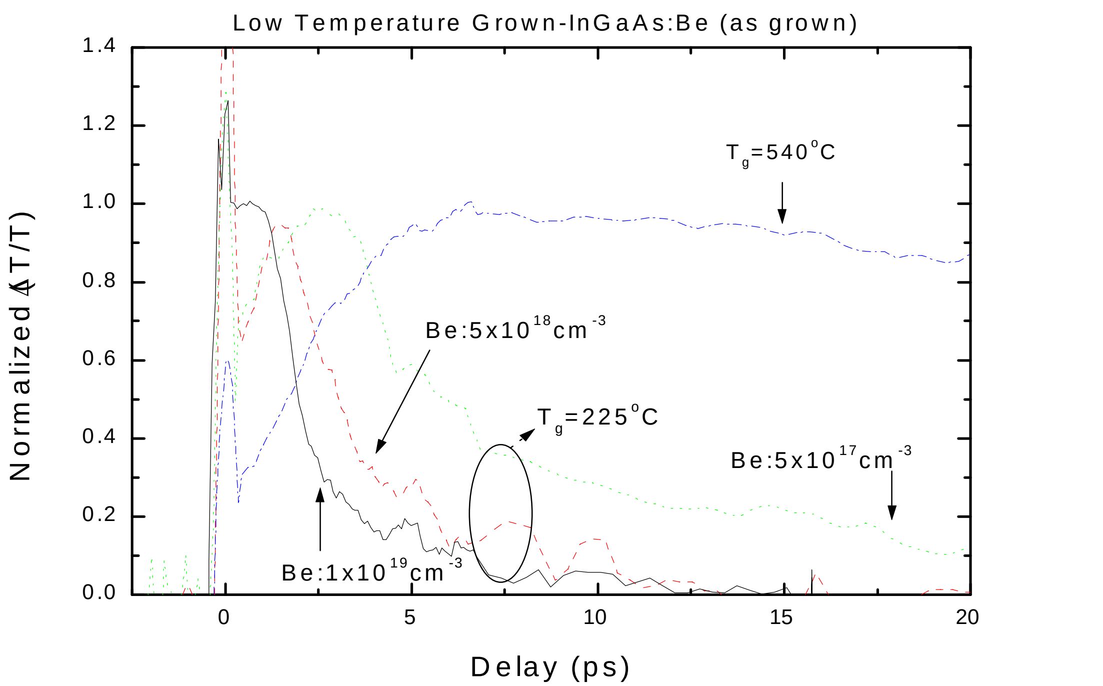

Figure 1. Normalized Transient THz transmission following the photo-excitation of low-temperature-grown (LTG) InGaAs. The material was grown at 225°C with $5x10^{17}cm^{-3}$, $5x10^{18}cm^{-3}$ and $1x10^{19}$ Be-doping under 15µTorr As-pressure and is not annealed (as-grown). The transient ΔT/T is proportional to the conductivity and is compared with the conductivity response of the standard temperature grown (STG) bulk InGaAs.

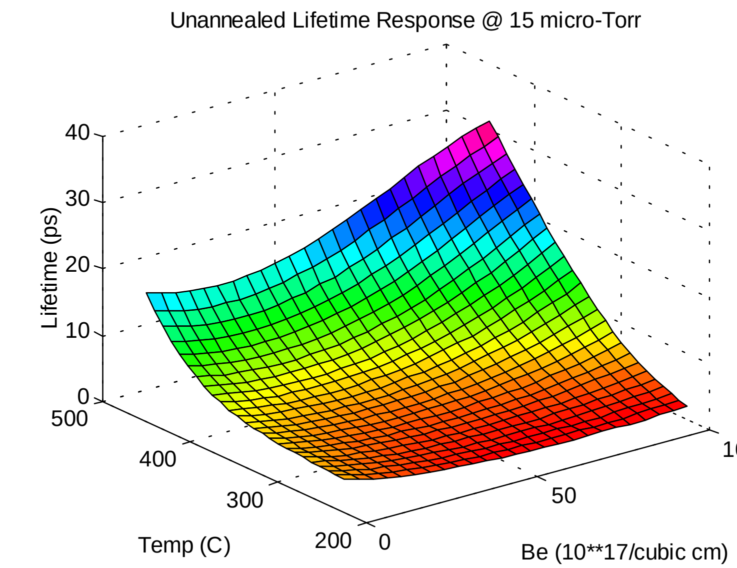

Figure 2. 3D contour of carrier lifetime as a function of growth temperature and Be doping. The contour is for as-grown material grown at 15 μTorr As overpressure. The contour was generated by a neural process model from data taken via time-resolved terahertz spectroscopy. Notice that carrier lifetime increases as the Be doping of the material increases.

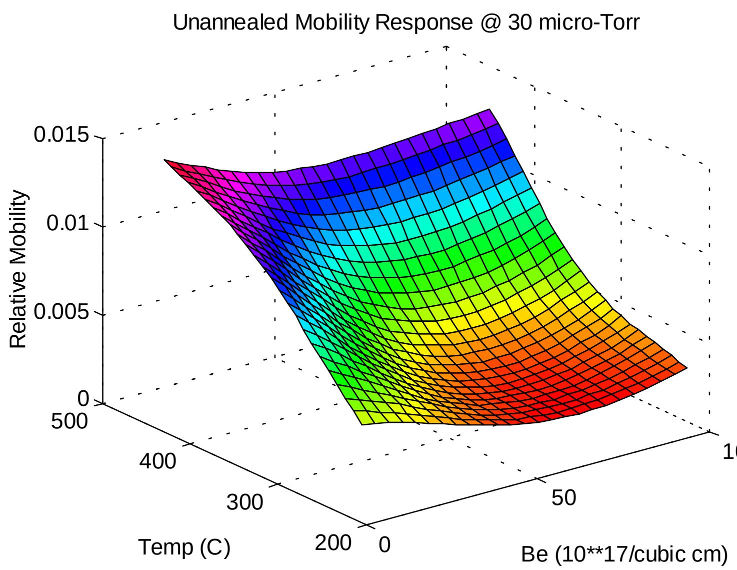

Figure 3. 3D contour of mobility as a function of growth temperature and Be doping for as-grown material at a constant As overpressure of 30 μTorr. The contour was generated by a neural process model from data taken via time-resolved terahertz spectroscopy. The growth temperature strongly influences the mobility.