# OBSERVATION OF AN ANOMALOUS MINORITY CARRIER TRAP IN N-TYPE InGaAs

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Temperature-dependent transient capacitance spectroscopy has revealed a deep hole trap in n-type $In_{0.53}Ga_{0.47}As$. Thermal activation and tunneling across the $p^+n$ junction are used to explain the unusual capture and escape mechanisms of this trap.

Lattice-matched $In_xGa_{1-x}As/InP$ ($x = 0.53$) heterostructures form the basis of a variety of optoelectronic devices operating in the 1.6μm communications band. Due to the technological significance of this system, growth of very high quality material is now commonplace. Nevertheless, physical defects are present in all semiconductors and are known to have a significant impact on device performance. Localized perturbations of the bonding configuration can lead to electronic energy levels deep within the bandgap that serve as carrier traps and/or efficient recombination centers, resulting in delayed response, restricted transport, loss of excitation, and localized heating. We have used temperature-dependent transient capacitance measurements, more commonly known as deep level transient spectroscopy (DLTS), to explore the distribution of defect levels in $In_{0.53}Ga_{0.47}As$ $p^+/n$ diodes.

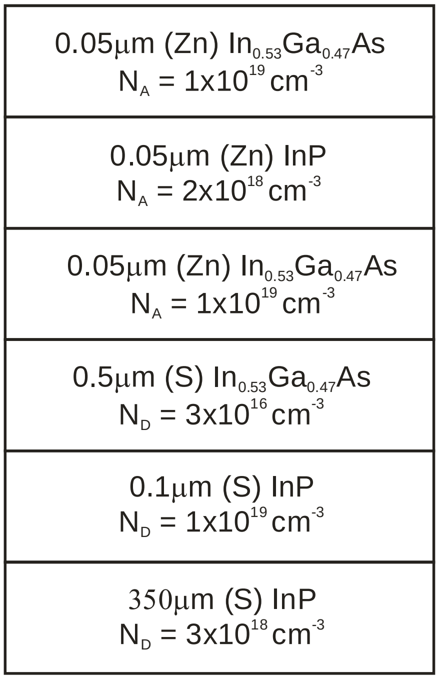

Fig. 1: MOVPE Device structure (not to scale).

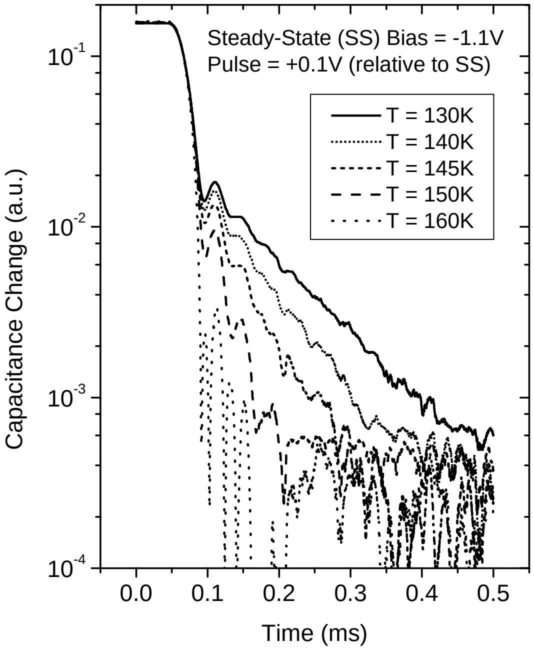

Fig. 2: Transient capacitance traces near the thermal activation temperature. The trace does not change appreciably for T < 130K.

The device structure is presented in Fig. 1 and several capacitance transients are shown in Fig. 2. Capacitance measurements are made with a Boonton 7200 Capacitance Meter, which uses a 1MHz test signal and has a response time of approximately 30μs. The sign of the capacitance transients indicates that minority carriers are being trapped during the +0.1V filling pulse when the bias is increased (i.e. made less negative). The observation of a minority carrier trap under reverse bias conditions is unusual, but may be explained by changes in the occupation of hole traps in the n-type material near the p+/n junction as shown in Fig. 3. A similar model has recently been proposed to account for minority carrier trapping in Schottky-barrier p-type GaAsN under reverse bias.[1] In our case, when the bias is increased the intersection of the trap level with the hole quasi-Fermi energy shifts away from the junction, permitting more holes to be trapped.

This model would also help to explain two additional features of our DLTS results. First, we observe a temperature independent escape mechanism at low temperature. As shown in Fig. 4, thermal activation out of the traps becomes less important with falling temperature, giving way to a constant

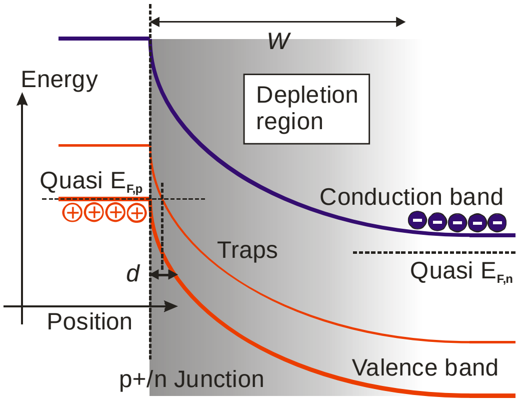

Fig. 3: Proposed model: *W* and *d* shift with applied bias.

escape time $\tau_{esc}$ of approximately 110 µs. In the context of the proposed model, we attribute this phenomenon to tunneling through the narrow (on the order of 10nm according to SimWindows[2] modeling) barrier that separates holes in the p-type region from the adjacent trap states. Theoretically, the dominant mechanism for barrier penetration switches from tunneling to thermal activation when $kT > \hbar / t_{trav}$, where $T$ is the temperature and $t_{trav}$ is the barrier traversal time.[3] Fig. 4 shows that, when the temperature independent mechanism is subtracted out, a thermal activation energy $E_a$ = 0.29eV is obtained. Hence, assuming a triangular barrier with a height of 0.29eV and a base thickness of 10nm, we obtain[4] a traversal time of $5\times10^{-14}$ seconds and a transition temperature of 145K, in good agreement with our experimental results.

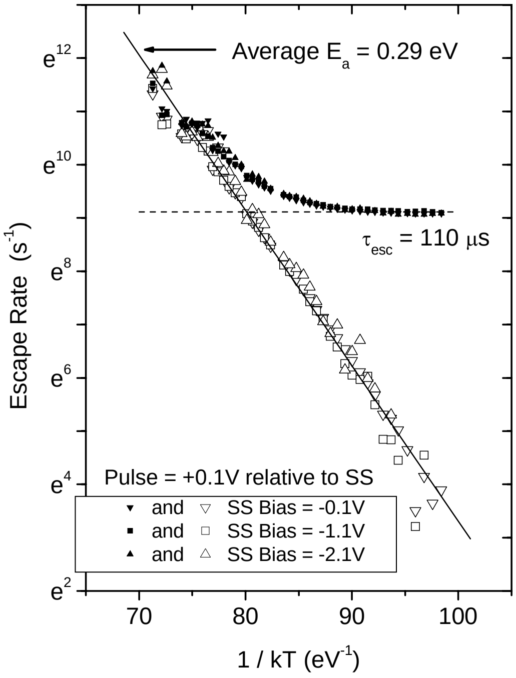

Fig. 4: Arrhenius plot of the escape process for the steady-state (SS) biases indicated in the caption. The solid symbols are the measured rates and the open symbols show the behavior when the temperature-independent rate (110 µs)$^{-1}$ is removed.

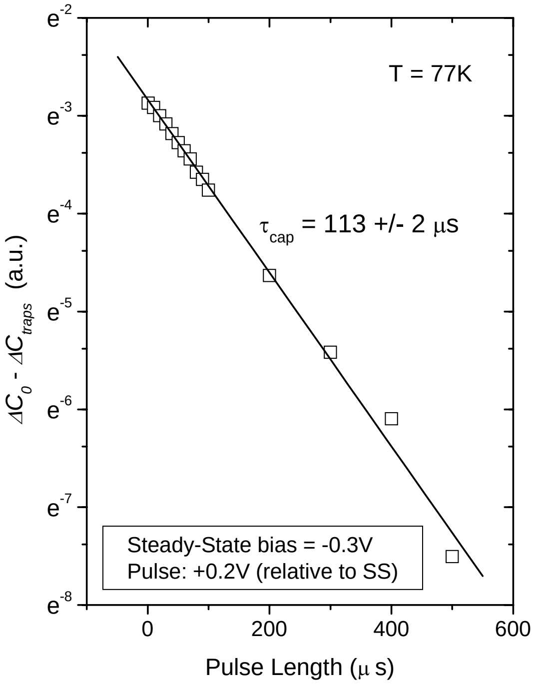

Fig. 5: The difference between the transient amplitude $\Delta C_{traps}$ and the saturated amplitude $\Delta C_0$ plotted against the length of the filling pulse.

Secondly, we note a puzzling symmetry between the trap capture and escape times. Let $\Delta C_{traps}(t)$ be the amplitude of the slow capacitance transient for a filling pulse of length $t$ and let $\Delta C_0$ be the saturated amplitude obtained with a suitably long filling pulse. Then $\Delta C_0 - \Delta C_{traps}(t)$ is proportional to the fraction of unfilled traps and the capture time $\tau_{cap}$ is obtained from the slope of the plot presented in Fig 5. We find that $\tau_{cap} \approx \tau_{esc}$, and in the context of the proposed model, we attribute this symmetry to the similarity of the barrier for the capture and escape processes.

In order to further test the validity of our model, we consider how $\Delta C_0$ depends on the applied bias $V$. We use SimWindows modeling to determine how $d$ changes with bias, yielding the thickness of material probed in each experiment. If the traps are located near the junction, we expect the saturated amplitude of the capacitance transient associated with these traps to scale with this thickness. Results of these calculations are shown in Fig. 6 along with a scaled measurement of $\Delta C_0(V)$. For comparison, we use our measurement of capacitance vs. voltage at $T = 145K$ to estimate how the depletion thickness $W$ changes with applied bias. If the trapping process is related to changes in trap occupation near the edge of the depletion region (as is usually the case in DLTS experiments), we would expect $\Delta C_0(V)$ to scale with this parameter. Since the transient amplitude follows the change in $d$ rather closely, and deviates considerably from the change in $W$, we conclude that our

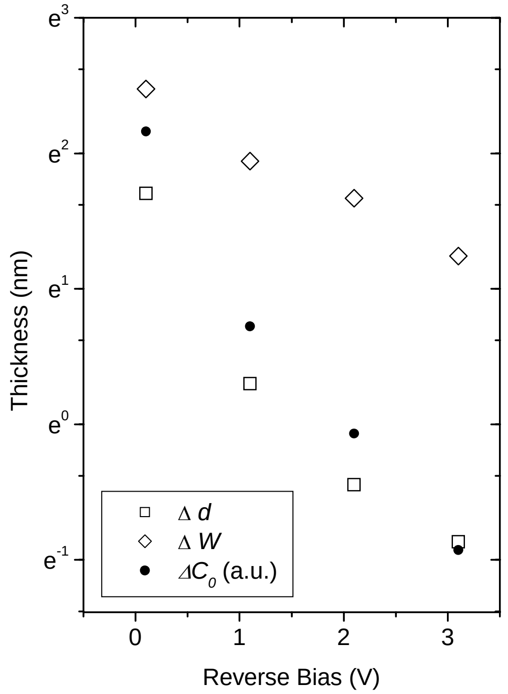

Fig. 6: Thickness of material probed near the p+/n junction $\Delta d$ and at the edge of the depletion region $\Delta W$ when a +0.1V bias pulse is applied to the device. Also shown is the amplitude of the capacitance transient $\Delta C_0$, scaled to the average of $\Delta d$ and $\Delta W$ at 0V.

model is correct: the minority carrier traps are located near (i.e. within tens of nanometers of) the p+/n junction.

Furthermore, we see that $\Delta d$ is on the same order as $\Delta W$, indicating that the volume of material probed near the junction is comparable to the volume of material scanned at the edge of the depletion region. Near zero bias at 77K, $\Delta d \approx \frac{1}{2}\Delta W$ and $\Delta C_{traps} \approx \frac{1}{3}\Delta C_{free}$, where $\Delta C_{free}$ and $\Delta C_{traps}$ are the amplitudes of the fast and slow components of the capacitance transient, respectively. Using the donor concentration $N_D = 3\times10^{16}\,cm^{-3}$ at the edge of the depletion region as determined from *C(V)* analysis, we estimate a trap concentration of approximately $2\times10^{16}\,cm^{-3}$.

The presence of such a high concentration of deep traps in this high quality material is surprising – our photovoltaic devices incorporating this alloy always perform very well. Hence, we hypothesize that these traps are not uniformly distributed throughout the n-type InGaAs, but are concentrated in the vicinity of the p+/n junction. This situation might result if the traps are related to interstitial Zn defects or other Zn-related complexes, since Zn diffuses rapidly in this alloy.[5] Indeed, secondary ion mass spectroscopy analysis on a similar structure shows that Zn diffuses tens of nanometers into the nominally n-type S-doped region during our MOVPE growth, which is consistent with the distances discussed here. We are currently testing this hypothesis by studying a series of new structures that are expected to have markedly different Zn concentration profiles near the p+/n junction.

Finally, we point out that photoluminescence experiments on similar but nominally undoped heterostructures reveal a broad sub-bandgap peak approximately 0.28 eV below the band-to-band emission.[6] The coincidence of this measurement with the activation energy deduced from our DLTS analysis is noteworthy, but a different model involving a deep donor level is required to explain the photoluminescence results. In particular, while the conduction band edge is predicted to shift with In concentration in bulk InGaAs,[7] our measured sub-bandgap transition energy does not. Hence, the observed transitions are attributed to a deep donor level and a level that tracks with the valence band, since these energies are expected to be nearly independent of alloy composition.

In conclusion, if the model proposed herein is correct, the situation could be expected to have a significant bearing on the operation of many InGaAs/InP-based optoelectronic devices, which depend on optical transitions between electronic states near a p/n junction within the InGaAs alloy. The junction is a critical component of the structure and the presence of a deep hole state near the junction would play an important role in the electro-optical activity of any such device.

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