Characterization of deep traps in semi-insulators by current transients

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Deep traps in semi-insulators (SI) are characterized using a junction composed of an epitaxial p-type layer grown on SI n-type layer. At a reverse bias electrons are released from the traps resulting in a current transient through the substrate. Simultaneously the depletion region in the epilayer expands until the entire layer is depleted leading to a decaying epitaxial current. The analysis of these transients renders the electron emission and capture coefficients and lifetime, and the energy location of the traps. The long current decay are accelerated by illuminating the sample with photons of energy below the band gap, as long as their energy is larger than the difference between trap energy and the bottom of the conduction band. Thus we determined *directly* this energy difference.

Semi-insulators (SI) are frequently used as substrates for advanced electronic devices. A semiconductor material becomes a semi-insulating material by the presence of high concentrations of impurities or defects, such as EL2 or Cr in GaAs,[1-3] deep within the forbidden gap. The characterization of these materials is extremely difficult due to their ultrahigh resistivity.

In this letter we suggest utilizing a junction between a p-type epitaxial layer and semi-insulating materials with EL2 as a test structure for characterization of the deep traps. Solomon and Weiser[4] have shown that in spite of the high resistance of the semi-insulating material, this junction is rectifying, i.e., at steady state the voltage drop appears across the depletion region. Two depletion regions are present in the epilayer, one at the surface and the other at the semiconductor-SI junction. As a result, in a properly designed structure, a narrow conducting path is left undepleted in the epi. The current through the epilayer, I_{EPI}, is therefore a sensitive measure of the extent of the depletion regions. The width of the junction depletion region can be changed by either varying the temperature of the sample or by illuminating it,[5] or by applying a bias to the junction. This bias results also in a current transient through the substrate, I_{SI} (perpendicular to I_{EPI}).

The experiments were performed by applying a reverse bias V_A to the substrate while simultaneously applying a probe voltage V_P, much smaller than V_A, along the epilayer. Transients of both currents, I_{EPI} and I_{SI}, were recorded. In a separate paper[6] we investigate the transient behavior of the semiconductor-SI junction. This formalism provides the tool for characterization of the energies and capture cross sections in semi-insulating materials. By measurements of the current transients one can derive these essential parameters. Both currents were recorded as a function of time in the temperature range of 230–300 K. Below 200 K the epitaxial layer is completely depleted at equilibrium.[7]

The test structures investigated are composed of an epitaxial p-type GaAs layer, with an acceptor concentration of 10^{15} cm^{-3}, grown by molecular beam epitaxy on a semi-insulating GaAs substrate. The concentration of EL2 traps is $N_T=2\times10^{16}$ cm^{-3}. Also present are shallow acceptors with a concentration of $N_{a_{\mathrm{SI}}}=2\times10^{15}$ cm^{-3}. As a result the substrate is slightly n type, with a typical equilibrium electron concentration of $\bar{n}_{\mathrm{SI}}=10^8$ cm^{-3} at room temperature. The compensation process results in an equilibrium ionized trap concentration $N_T-n_{T0}=N_{a_{\mathrm{SI}}}$, where n_{T0} is the equilibrium concentration of occupied traps. The epitaxial layer is 1.5 μm thick (d) and the substrate is 400 μm thick (L).

At equilibrium there is a minimal depletion region within the SI which is completely depleted from electrons, i.e. the traps are fully ionized and the positive space charge density is 2×10^{16} cm^{-3}. As the bias voltage is applied a second region is generated in the SI which is initially depleted only from free electrons. As a result a *net* release of electrons from traps takes place, gradually increasing the space charge density. Eventually, the partially depleted region collapses resulting in a wider full depletion region.

The transition processes in the SI can be derived from measurements of the current through it I_{SI}. Since this current is orders of magnitude larger than the saturation current of this structure, the role of holes in this current is negligible. It is generated by the net release of electrons by the donorlike traps (EL2). An equal amount of charges recombine in the epilayer. The net recombination in the epilayer results in narrowing of its conducting path. Therefore the time derivative of the conductance is proportional to I_{SI}. Indeed, an excellent fit between I_{SI} and the time derivative of I_{EPI} was shown experimentally.[6] Thus we have just shown that rather than measuring I_{SI}, which is in the range of nanoamperes or less, one can measure the current along the epilayer I_{EPI}, microamperes in magnitude. Since the width of the epilayer is small to begin with, the conductance of this layer is very sensitive to these changes.

The total charge in the space charge of the partially depleted region of the SI, $Q(t)$, equals the amount of unoccupied traps (beyond those compensated by shallow acceptors). A theoretical value for $Q(t)$ can be obtained by solving the continuity equation for this region. A detailed solution is given elsewhere.[6] Since there is a net release of electrons in the depletion region, $Q(t)$ increases exponentially as $[1-\exp(-e_nt)]$, where e_n is the emission coefficient of the traps. Thus $Q(t)$ is given by

$$Q(t)=qAx_p(t)[n_{T0}-n_T(t)]=qAx_p(t)n_{T0}[1-\exp(-e_nt)], \quad (1)$$

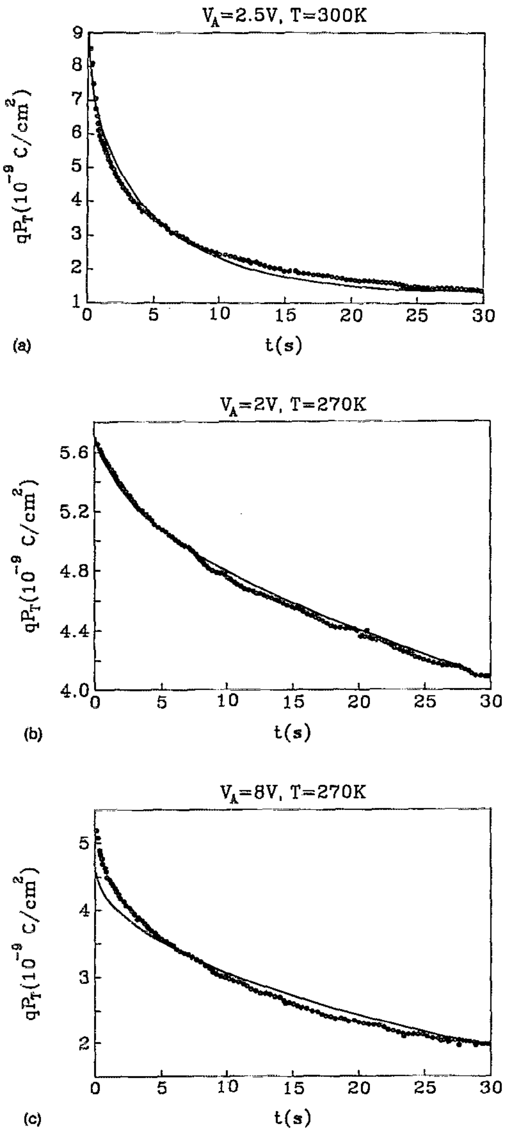

FIG. 1. Calculated (solid line) and measured (circle) decay of epitaxial charge qP_T. (a) T=300 K, V_A=2.5 V; (b) T=270 K, V_A=2 V; (c) T=270 K, V_A=8 V.

where A is the cross-section area, and n_{T0} is the initial concentration of occupied traps. In the case of a thin epilayer only a part of the carriers recombine in this layer and the charge density is multiplied by this fraction. This numerical correction has no implication on the technique and therefore is left to the full analysis.[6] The width of the partially depleted area, $x_p(t)$, is obtained from the following differential equation:[6]

$$\frac{dx_p}{dt}(1-e^{-e_nt})+e_nx_pe^{-e_nt}$$

$$=\left[\left(V_A-\frac{qn_{T0}}{2\epsilon_0\epsilon_r}(1-e^{-e_nt})x_p(t)^2\right)\Big/L\right]\frac{\bar{n}_{SI}}{n_{T0}}\ \mu_n. \qquad (2)$$

The boundary value is $x_p(t=0)=\mu_nE_A\tau_n$, the drift length, where μ_n is the electron mobility, $E_A=V_A/L$, and τ_n is the electron lifetime dominated by the trapping process.

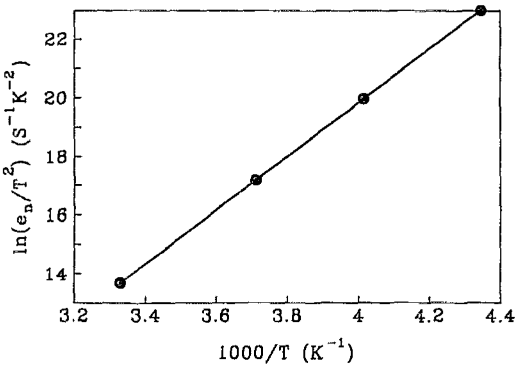

FIG. 2. Arrhenius plot.

The volume of *net* release of carriers decreases resulting in a decay of the substrate current. The current through the epilayer, I_{EPI}, is proportional to the total hole concentration in the layer, $P_T(t)$, given by the integral on the local hole

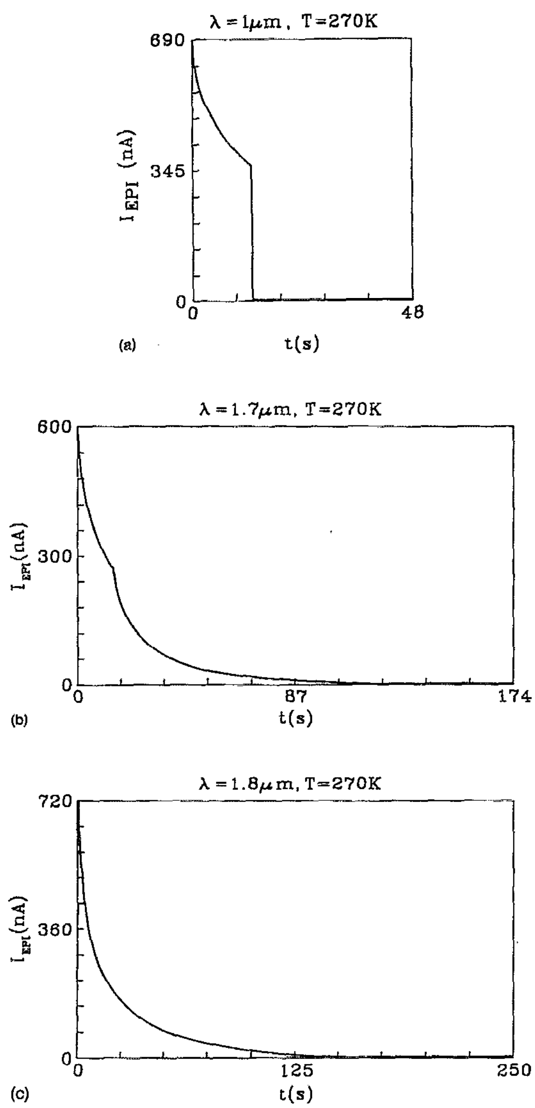

FIG. 3. Epicurrent transients before and after illumination, T=270 K. (a) λ=1.0 μm; (b)λ=1.7 μm; (c) λ=1.8 μm.

concentration $p(x,t)$ over its thickness d. For a sample of length l and width w this current is given by

$$I_{\mathrm{EPI}}(t)=q\mu_p \frac{w}{l} V_P\int_0^d p(x,t)dx=q\mu_p \frac{w}{l} V_P P_T(t). \quad (3)$$

On the other hand, the change in $P_T(t)$ equals to $Q(t)$, i.e.,

$$Q(t)=qA[P_T(0)-P_T(t)]. \quad (4)$$

From the numerical solution of Eq. (2) $x_p(t)$ is inserted into Eq. (1) out of which $Q(t)$ is obtained and therefore $P_T(t)$. The value of $P_T(0)$ is derived from the equilibrium widths of the two depletion regions.[7] Thus it is possible to compare the theoretical $P_T(t)$ with that derived from the measured data of I_{EPI} by Eq. (3). The results are shown in Fig. 1 for the temperature range of 270–300 K for various bias voltages to the substrate V_A. The fit to theory is very good. At lower temperatures the data are noisier due to the extremely long emission time (of the order of 10^{15} s) and due to the fact that the epilayer is almost completely depleted at equilibrium. For larger bias voltages the initial "partial" region is wider, therefore the generation current is proportionally larger. Thus the transient is shorter.

The only adjustable parameter in the fit of the P_T data is the electron emission coefficient e_n. The values derived agree well with those obtained by deep level transient spectroscopy (DLTS) in non-semi-insulating material.[1,8] An Arrhenius plot is shown in Fig. 2. The activation energy extracted is 0.77 eV. This value is not exactly E_C-E_T since one actually measures the change in enthalpy plus the temperature dependence of the capture cross section.[9] Still this energy is within the values derived from DLTS measurements.[1,8] The electron lifetime is derived from $\tau_n=\bar{n}_{\mathrm{SI}}/e_n n_{T0}$ while the capture coefficient is obtained from $c_n=1/\tau_n(N_T-n_{T0})$.

The transients of a semiconductor-SI junction are very long. These transients can be shortened drastically by illuminating the SI through the semiconductor with photons of energy below the band gap. These photons are not absorbed by the epilayer, however, if their energy is large enough to excite electrons from the traps into the conduction band, the process of the collapsing of the partially depleted region into the full depletion can be accelerated significantly. As the energy of the illuminating photons is increased, the absorption coefficient increases and therefore the shortening of the transient is more effective. For wavelengths shorter than 1.3 μm the photons are energetic enough to excite electrons into the L_6 valley thus an additional increase of the absorption is observed. On the other hand, while increasing photon wavelength a point is reached where the photon energy is below E_C-E_T and no change in the transient is observed. Hence this technique serves to determine directly this energy difference, and not indirectly such as by activation energies [which may be complicated by thermodynamic arguments described above (Ref. 9)].

To that end the structures were placed in a cryostat with an optical window which was attached to an infrared monochromator. The epilayer current I_{EPI} was recorded as the voltage biases were applied and once it fell to about half its initial value the device was exposed to the monochromator. The transients were recorded with excitation wavelengths in the range of 1.0–1.8 μm. Figure 3 shows the current through the epilayer I_P as a function of time. While the accelerated decay is very pronounced at shorter wavelengths, it disappears at a wavelength of 1.8 μm. This experiment verifies that indeed the EL2 traps in the SI are located 0.68 eV below the bottom of the conduction band.

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