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Investigation of Trapping in Iodine Single Crystals by Repeating Carrier Injection*

M. SIMHONY† AND A. SHAULOF
Department of Physics, The Hebrew University, Jerusalem, Israel
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Free holes generated on the illuminated surface of an iodine crystal are injected into its bulk by applied voltage pulses. The space-charge-limited currents obtained with sequential pulses at various voltages and with different time intervals between the pulses allow one to calculate the density of trapped charge and the characteristic time constants of trapping and release. It is also possible to estimate the concentration of trapping levels, their capture cross section, and their energy position in the forbidden gap, in good agreement with previous results.

INTRODUCTION

IN a well-relaxed insulating crystal the space-charge-limited current (SCLC) obtained at the onset of an injecting voltage pulse is reasonably near the same as in the ideal trap-free case.[1–3] During the pulse, a part of the injected charge is trapped and causes the transient SCLC to decrease towards a steady-state value which is less than in the ideal case by a factor Θ, ($\Theta \ll 1$). From the decay of the transient SCLC, the characteristic time constants τ of two trapping processes can be evaluated in iodine single crystals[4,5]; one is fast, with τ in the 0.1-msec range, the other is much slower, its τ being in the range of 10 to 100 msec. To obtain the slow-trapping characteristics one has therefore to expose the sample to a prolonged action of voltage and light; thus polarization and heating complicate the analysis.

In the present work, slow trapping is investigated by using a sequence of comparatively short voltage pulses.[6] The first pulse is applied to a relaxed sample, and during its propagation the traps become partially filled. The second pulse rises after a time interval Δt which is shorter than the emptying time of the traps; the observed SCLC is thus affected by the instantaneous field of the trapped charge. By varying the height and length of the applied pulses and changing the time interval between them, one obtains information about the occupancy and concentration of the traps, their energy location, and characteristic time constants.

EXPERIMENTAL TECHNIQUE

The samples were single-crystal wafers of 0.5 cm² in area and thickness 0.1–0.2 cm, grown from purified iodine.[5] The sample preparation and the measuring apparatus have been described earlier.[2,4] One surface of the sample was illuminated (through a transparent electrode) with strongly absorbed light which created an "infinite" reservoir of free carriers near the surface. The layer served as an injecting anode when a square voltage pulse (duration 1–30 msec, 100–1000 V in amplitude) of proper polarity was applied. An automatic trigger fired a second pulse at any desired moment between 50 and 500 msec after the collapse of the first one. The time interval between sequential pulses could also be changed by the choice of a pulse-repetition frequency (1, 2, 4, 8, or 50 pulse/sec).

THEORY

Consider an insulating crystal of length L in the x direction, having a spatially uniform distribution of two kinds of shallow traps,[7] fast and slow. These are characterized by trapping times τ' and τ, correspondingly ($\tau \gg \tau'$), and are empty at the beginning of the experiment. Under an applied voltage V free holes are injected at the anode ($x=0$), a transient SCLC flows to the cathode ($x=L$), and the traps become partially filled. At a moment $t=-\Delta t$ the voltage pulse collapses and the holes which are thermally released from traps now leave the sample through the electrodes. After a while trapped charge remains only on the slow levels, and its spatially uniform density p_t decreases exponentially with a characteristic release time τ_r. Now at a moment $t=0$ the voltage pulse is applied again, the time interval between this second pulse and the end of the first one being comparable with τ_r. The density of the resulting transient SCLC at any point x of the crystal (diffusion neglected) is

$$j_2(t)=\epsilon\,\partial E(x,t)/\partial t+q\mu p E(x,t)\,. \qquad (1)$$

Here ϵ is the dielectric constant ($\epsilon=\epsilon_0\kappa$, *mks* units), E is the electric field, p is the density of the injected free holes, μ is their mobility, and q is the electronic charge. Poisson's equation is

$$\partial E(x,t)/\partial x=(q/\epsilon)[p(x,t)+p_t]\,. \qquad (2)$$

For $0\leq t\lesssim t^*$, where t^* is the transit time of the leading

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front of injected holes, $t^* < \tau' \ll \tau$, the trapped charge is only that left over from the first pulse, and its density p_t remains substantially constant. Thus, proceeding exactly as in Ref. 2, we obtain

$$j_2(t) = \epsilon\mu E^2(L,t)/2L - q\mu p_t V/L. \quad (3)$$

The calculation of the field at the cathode $E(L,t)$ is complicated and will not be presented here; therefore we cannot write the final expressions for t^* (from $\int_0^{t^*} \mu E(L,t)dt = L$) and for $j(t)$. However, one can easily calculate the field at the cathode at the onset of the second pulse, because then $p=0$ everywhere in the sample, except at $x=0$, and Poisson's equation is $dE(x,0)/dx = qp_t/\epsilon$. Using the fact that $\int_0^L Edx = V$, and that $E(0,t)=0$ (infinite carrier reservoir), one obtains

$$E(L,0) = (V+V_t)/L, \quad (4)$$

where $V_t = qp_tL^2/2\epsilon$. Substitution into Eq. 3 yields

$$j_2(0) = \epsilon\mu(V-V_t)^2/2L^3. \quad (5)$$

Comparison with the corresponding expression for the trap-free case, $j_1(0) = \epsilon\mu V^2/2L^3$, shows that the effect of trapped charge on the initial SCLC is in lowering the effective applied voltage by an amount V_t. Obviously, V_t is the voltage produced at the anode (or cathode) by a layer of space charge having uniform density p_t, which extends throughout the sample. For the density of trapped charge one obtains now

$$p_t = aV[1-(j_2/j_1)^{1/2}],$$

or

$$p_t = a(V-bj_2^{1/2}), \quad (6)$$

where a and b are sample constants, $a = 2\epsilon/qL^2$, $b = (2L^3/\epsilon\mu)^{1/2}$.

The time constant τ_r of the thermal release from traps is[8] $\tau_r = [vS_pN_v \exp(-\mathcal{E}_{tv}/kT)]^{-1}$, where v is the thermal velocity of carriers, S_p is the capture cross section of the traps, $\mathcal{E}_{tv}$ is their energy distance from the valence band, and N_v is the effective density of states there. The trapping time is $\tau = (vS_pN_t)^{-1}$, N_t being the concentration of traps. Thus,

$$\tau/\tau_r = (N_v/N_t)\exp(-\mathcal{E}_{tv}/kT) = \Theta, \quad (7)$$

where Θ is the steady-state ratio of the free-hole density to the density of all the injected charge,[7] $\Theta \equiv \bar{p}/(\bar{p}+\bar{p}_t) \approx \bar{p}/\bar{p}_t$. The values of τ and Θ are obtained from the decay of transient SCLC to a steady state,[4,5,9] and Eq. (7) may be useful in cross-checking them. Having an estimate of N_v one can also use this equation to determine $\mathcal{E}_{tv}$, because N_t may be found independently as the high-voltage saturation value of the density of trapped charge at the end of the first pulse.

EXPERIMENTAL RESULTS

Figure 1 shows oscillograms of transient SCLC obtained with pairs of voltage pulses. The upper line is a group of 4 first-pulse traces, each of them taken 2–15 minutes after the foregoing excitation. Their coincidence implies that they were fired when the traps were essentially empty; one may also conclude that 2 min is a sufficient waiting time to satisfy this condition. After the collapse of each of these pulses a second pulse is automatically triggered with a time interval $\Delta t = 50$, 150, 250, 350 msec. The corresponding four traces are nearer to the first-pulse trace, the larger Δt is, because the more holes were freed from traps and the opposing field of trapped charge is weaker.

Such oscillograms were taken for a number of samples at different voltages. The initial current values $j_2(0)$

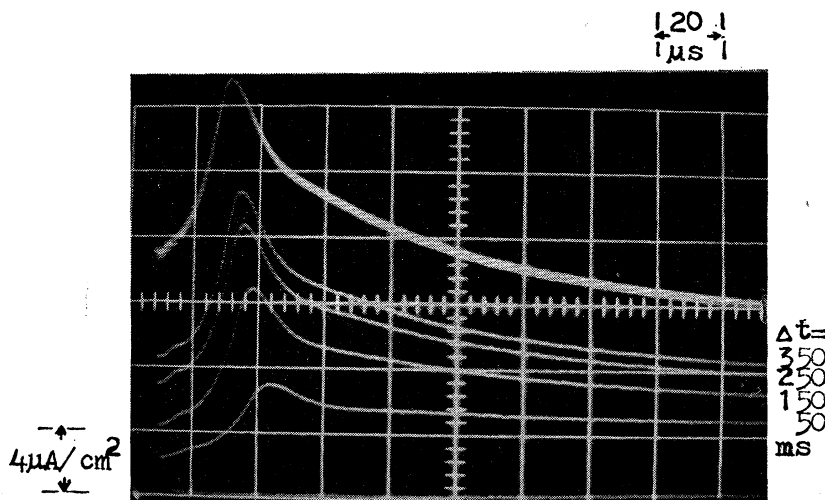

FIG. 1. Oscillograms of transient SCLC obtained by repeating carrier injection. The upper line is a bunch of first-pulse traces; next are traces obtained with intervals of 350, 250, 150, and 50 msec, respectively. The applied voltage is 500 V, and the sample thickness is 0.12 cm.

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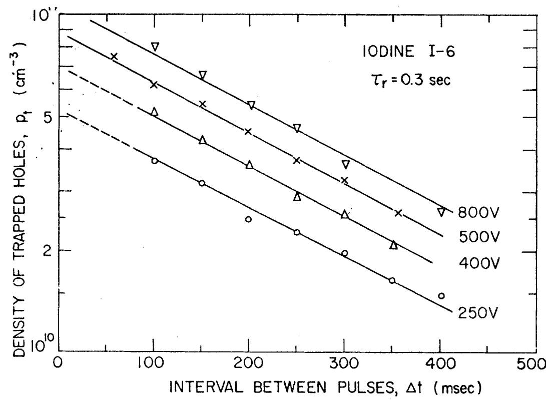

Fig. 2. The time dependence of the density of trapped holes after the collapse of the voltage pulse.

from the oscillograms were used to calculate the density p_t of trapped charge according to Eq. 6. Figure 2 shows these values for a particular sample, plotted in a semilog scale against Δt. The slopes for all the four different voltages are essentially the same and yield

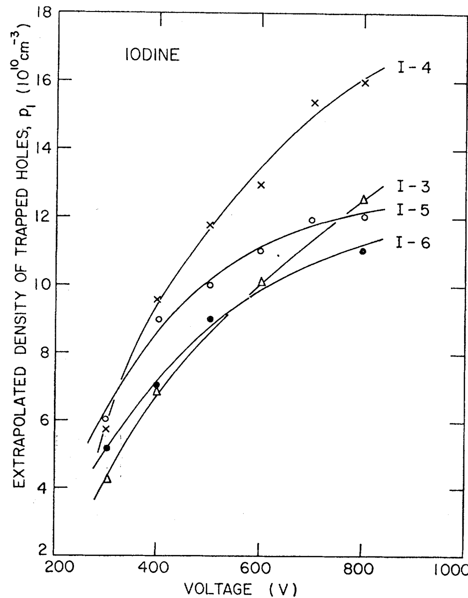

Fig. 3. Voltage dependence of the density p_1 of holes trapped in slow levels at the end of the first pulse.

the time constant τ_r of the thermal release from traps, $\tau_r=0.3$ sec. Extrapolation of the plots to $t=0$ obviously yields the density p_1 of trapped charge on the slow levels at the end of the first pulse. In the other three samples the values of τ_r are 0.7, 0.9, 0.6 sec (samples #3, 4, 5, respectively).

The p_1 values for four samples are plotted against applied voltage in Fig. 3. A tendency to saturation is seen which allows estimating the concentration of traps N_t; N_t seems to be between 10^{11} and 2×10^{11}. Because the typical Θ values are 0.02–0.05, one obtains for the trapping time, $\tau=\tau_r\Theta$, the values 5–50 msec, in good agreement with those found from the decay of the first pulse to a steady state. The values of τ and N_t yield for the capture cross section S_p of the traps 10^{-16}–10^{-15} cm^2. Taking $N_v=10^{21}$ cm^{-3} (iodine being a molecular crystal) and using Eq. (7), we obtain $\mathcal{E}_{tv}=0.6$ eV. The same value was obtained in the measurement of the thermal activation energy of the traps.[4]

The transit time t^* is seen (Fig. 1) to be longer for smaller Δt. Obviously, the field of trapped charge inhibits the motion of injected holes up to the middle plane of the sample. Although in the second-half of the crystal the holes are aided by the field of the trapped charge as much as they are opposed in the first-half, the time average of their velocity is lowered since they spend more time in the first-half of the crystal. It is also worth noting that the shorter Δt the closer is the shape of the current trace to that in the trap-free case[2,9] (the maximum current value is closer to $2.72j(0)$; at $t\gg2t^*$, the current has a nearly constant value of $\sim2.25j(0)$) for an applied voltage of V-V_t. The reason is that as more traps are filled at the beginning of the pulse, a smaller part of the injected holes is trapped.[6]

We conclude that the method of repeated carrier injection yields the characteristic parameters of trapping for both transient and steady-state conditions without exposing the sample to prolonged action of voltage and light, and may be useful in investigating trapping processes.

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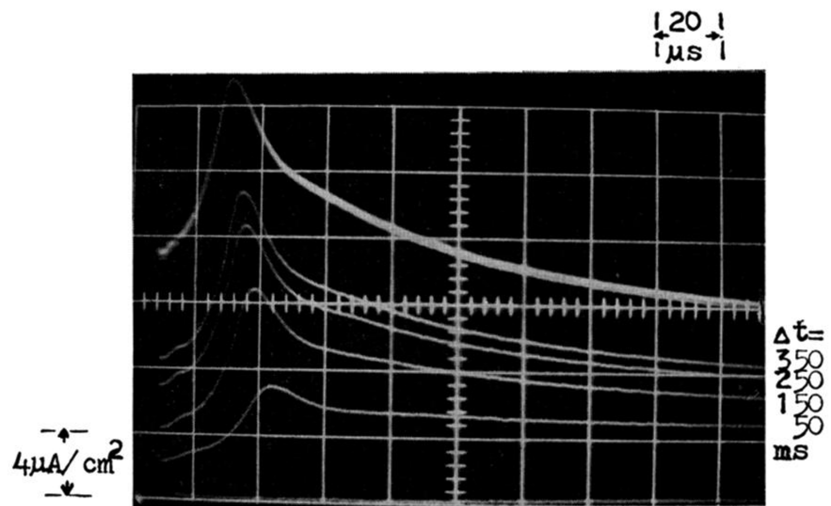

FIG. 1. Oscillograms of transient SCLC obtained by repeating carrier injection. The upper line is a bunch of first-pulse traces; next are traces obtained with intervals of 350, 250, 150, and 50 msec, respectively. The applied voltage is 500 V, and the sample thickness is 0.12 cm.