Anomalies in the electronic time-of-flight current traces in sulfur

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In a previous paper we presented a model aimed at explaining two anomalous effects observed in the measurements of the time-of-flight electronic current in sulfur generated by a pulse of light. These effects consisted of a fast initial decay and a long-lived tail in the current trace for sulfur samples that were submitted to a pulse of light while also subjected to an electric field. They were explained as having the same origin, namely, that light was assumed to excite carriers not only into a normal channel with a constant mobility but also into a second one whose carrier mobility decreased exponentially with the distance (depth) from the surface the carrier was at. Such a dependence would then give rise to both the fast initial decay and the tail. In this paper we show results of experiments that contradict the earlier conclusion. Two kinds of experiment have been used: in the first one, an electric field was applied at increasing times after the pulse and in the second one, the electric field was reversed after the main transit of the carriers. The results of both types of experiment unequivocally show that the mentioned anomalies do not have a common origin and that the long tail seems, rather, to result from a delayed injection.

I. INTRODUCTION

The current traces in time-of-flight measurements of almost unperturbed electron packets in orthorhombic sulfur along the [111] direction show three kinds of anomaly which cannot be explained by normal trapping effects. Two of them are a fast initial decay, and a long-lived and somewhat noisy tail (comparable with the transit time). In Ref. 1 a model was presented that could explain the appearance of these anomalies by assuming that in addition to the normal, constant bulk mobility channel, there existed a surface channel characterized by a mobility that decreases exponentially with the depth of the carrier position inside the sample. Carriers created by light in the sulfur sample would populate both channels. The surface channel would give rise to a hyperbolically decaying current, which would explain, at the same time, the fast initial decay and the long-lived tail. Superimposed trapping effects would be present in the normal channel as well as in the surface channel.

In this paper we report results obtained with two kinds of measurement that contradict the model developed in Ref. 1. The techniques employed were the following. (1) The surface recombination technique (SRT), which is the same employed by Dolezalek and Spear[4] in order to study the electron-hole surface recombination in sulfur. In this technique the field is applied at different instants after the flash of light. The time elapsed between the flash and the application of the field is termed here as the pausing time, Δt. We were also able to measure the external current, from which the charge surviving recombination after a pausing time Δt was found by multiplying the extrapolated value of the initial current by the transit time. (2) The second technique is the inverted field technique (IFT), which is essentially the same as the classical time-of-flight technique,[1-3] with the difference that here the electric field was inverted after the main transit of the packet.

The results presented here were obtained with a 2.2-mm-thick sample with 1 cm^2 of area, and essentially in the same apparatus used in Ref. 1. Circuitry, however, was improved by using a differential amplifier that operated between two samples,[4] one of which received the light signal. We were able to measure currents as low as 2×10^{-11} A with a response time of 2 ms. Though the recombination process is not essential for the main findings of the work to be reported here, we have nevertheless obtained recombination constants under various conditions, in order to compare with the literature. The recombination coefficient was found to be reasonably independent of the applied field, and assumed the values of 1.0×10^{-10}, 1.5×10^{-10}, and 1.6×10^{-10} cm^3/s at 29 °C, 40 °C, and 45 °C, respectively. These values are of the order of magnitude predicted by a Langevin recombination of uniformly distributed free electrons with trapped holes, as assumed by Dolezalek and Spear.[4] A distance of ~ 1 μm was used which corresponds to the penetration of light.

II. RESULTS

Figure 1 shows seven current traces obtained with an electric field of 590 kV/m at 29 °C, and for pausing times ΔT ranging from $\Delta t = 0.41$ ms (curve *a*) to $\Delta t = 18$ ms (curve *g*). As will be seen later, it is convenient to choose the origin in the time axis as the instant at which the very short light flash (10 ns) was applied. The charge produced by the light flash amounted to $\sim 12\%$ of the product capacitance times voltage (CV) when the field was ap-

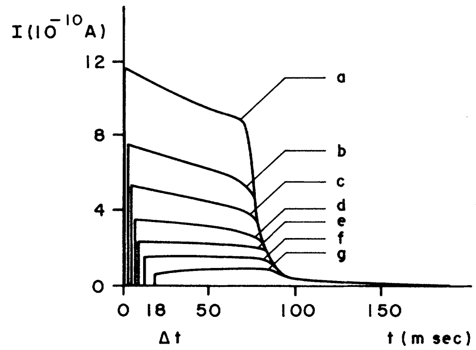

FIG. 1. Current traces obtained with the SRT, for varying pausing times Δt, which is the time elapsed between the flash and the application of the electric field. The values of Δt are 0.41 ms (curve *a*), 1.45 ms (*b*), 3.9 ms (*c*), 5.5 ms (*d*), 7.8 ms (*e*), 11.5 (*f*), and 18 ms (*g*). The origin of the time scale corresponds to the instant the light was flashed. Note the monotonic decrease of the current and the common long-lived tail in the traces.

plied before the flash. In this respect we observe that the extrapolated charge (obtained in each case by the product of the current by the transit time) is only 5% of CV. This indicates that the net charge generation is increased if the field had been applied before the flash because charge carrier recombination is reduced.

The traces in Fig. 1 display interesting features. The decreasing trend shown in curve a becomes progressively less pronounced for curve *b*, *c*, *d*, and *e*. Curve *g*, on the contrary, shows an increasing trend. Another interesting point is that the tails of all curves coincide if the origin is chosen at the instant the flash is lighted. Currents obtained for other values of the electric field gave results which showed essentially the same features of Fig. 1.

Figure 2 shows the results obtained with the IFT at

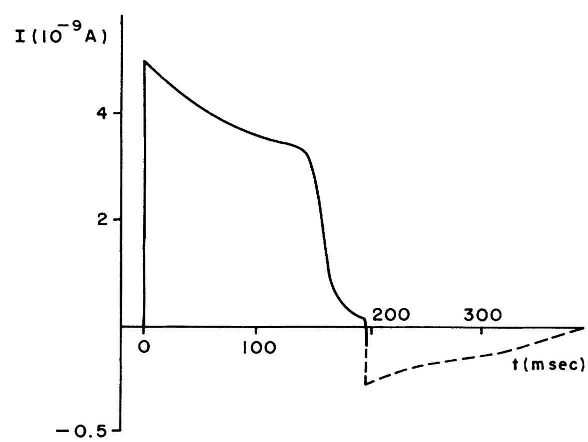

FIG. 2. Current traces with the IFT, where the inversion of the field was performed after the main transit of the normal carriers. Note that the scale of the dashed return (negative) current is four times enlarged, and the dispersive trend of the reversed signal.

29 °C and $0.05CV$. The applied electric field was (320 kV/m) and was inverted, as can be seen in the figure, some tens of milliseconds after the main transit of the packet, which is only a few milliseconds before the complete transit of the main packet. A decreasing reverse current was then observed. For the sake of clarity, this curve has been enlarged four times, as can be noted from the difference between the scales of the positive and negative directions in the current axis. This reverse current lasts approximately a transit time.

III. DISCUSSION

An inspection of Fig. 1 shows that the fast initial decay and the long tail after the main transit time are not correlated as had been assumed in the surface channel model of Ref. 1. While the long tail is independent of the pausing times ΔT, the current shapes, including the initial trend, are strongly dependent on them. In fact, the long tail coincides in all measurements if the origin in the time axis is chosen at the flashing time, which appears to indicate that it is rather correlated with the pulse of light, as will soon be explained. Note also that the transit time in all the traces of Fig. 1 is the same if we count from the instant at which the field was applied to the time corresponding to the half of the tail, and where the long tail was ignored.

An analysis of curve *g* can throw some more light on the mechanisms involved. It corresponds to the smallest initially injected charge, and allows us to observe that the whole process differs significantly from the one prevailing for curve *a* (which looks like a normal trace). The increasing trend and the coincidence of the tail when counted from the flashing time indicate that here a retarded emission of electrons from the surface is taking place. In this way we conclude that not only electrons surviving recombination are driven to the bulk when the electric field is on, but also other electrons which boil out of the surface giving rise to the long-lived tail. Their origin could be traced to surface dissociation of bulk created excitons[5] or detrapping of surface trapped electrons.

The results from the SRT discussed above are corroborated by the results obtained with the IFT. We go even further by proving mathematically (see the Appendix) that the surface channel as predicted in the model of Ref. 1 leads to wrong predictions for the IFT experimental results. According to the latter model, the long tail would be due to a packet of carriers still moving within the sample with a decreasing mobility after the main transit of the "normal carriers." If the field were then inverted, only those extra carriers would contribute to the current and an increasing current (with time) should be expected as clearly demonstrated in the Appendix. Contrary to this prediction, the current decreases (in modulus) mainly to the loss of carriers through the previous entrance electrode. If we assume that the charge boiling there started being injected just after the field was applied, its front would have already reached the other electrode. The reverse current should then last a transit time, about 160 ms, which is fairly well confirmed by the dashed line in Fig. 2.

We then conclude that the results from both SRT and IFT indicate that the tail is originated from a retarded surface emission,[6,7] and not as a result of a slow-moving second packet in a surface channel. Probably, this delayed injection cannot explain the fast initial decay, and therefore a second channel in communication with large cross-section traps should be invoked.

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APPENDIX

According to Ref. 1 the extra packet moves with a depth x-dependent mobility μ as

$$\mu=\mu_0 e^{-\alpha x} , \tag{A1}$$

where μ_0 and α are constants.

If E is the electric field and t is the time, we have

$$\frac{dx}{dt}=\mu E , \tag{A2}$$

and the position x_0 at the time t_0 after injection is given by

$$e^{\alpha x_0}=\mu_0\alpha E t_0+1 . \tag{A3}$$

If the field is now inverted, conserving its modulus, we obtain for the position x at a time t, using again Eqs. (A1) and (A2),

$$e^{\alpha x}-e^{\alpha x_0}=-\mu_0\alpha E(t-t_0) . \tag{A4}$$

Using Eq. (A3), we get

$$e^{\alpha x}=1+\mu_0\alpha E(2t_0-t) . \tag{A5}$$

Let A be the sample area and d be the sample thickness; the current $I(t)$ is then

$$I(t)=\frac{A\int_0^d \mu(x)\rho(x,t)E\,dx}{d} \tag{A6}$$

and owing to the δ-function nature of the charge density $\rho(x,t)$ we readily obtain

$$I(t)=\frac{\mu_0 q(0)e^{-t/\tau}E}{1+\mu_0\alpha E(2t_0-t)} , \quad t>t_0 , \tag{A7}$$

where $q(0)$ is the initial charge in the extra channel and τ is the trapping time. Finding $I(t_0)$ in order to eliminate $\mu_0 q(0)$, we finally obtain

$$I(t)=I(0)\frac{1+\mu_0\alpha E t_0}{1+\mu_0\alpha E(2t_0-t)} , \quad t>t_0 . \tag{A8}$$

Taking the values $\mu_0\alpha=5.3\times10^{-5}$ m/V s, $\tau=0.54$ s, and $E=318$ kV/m from Ref. 1, and $t_0=0.20$ from Fig. 2, we obtain from Eq. (A8) an increasing current. For instance, for $t=0.25$ s, $I(0.25)/I(0.20)=1.1$; for $t=0.35$, the ratio $I(0.35)/I(0.20)$ is 1.80, in complete disagreement with the dashed trace in Fig. 2.

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