MEASUREMENT OF MOBILITY IN AMORPHOUS SILICON USING TRAVELING WAVES

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ABSTRACT

We report a new method to measure low carrier mobilities in amorphous thin films using the acousto-electric effect. Mobilities as low as .08 cm^2/V-sec have been measured and we believe that still lower values down to .001 cm^2/V-sec can be measured. A traveling wave electric field is generated in the film by placing it close to a piezoelectric solid carrying surface acoustic waves. The charge carriers in the film are dragged along by the traveling wave and this effect is detected as a dc current in an external circuit. In our experiments, the external bucking voltage needed to null out this current is measured (thus eliminating contact resistance problems). This voltage is proportional to the carrier mobility, independent of the number of carriers. The mobility is thus calculated directly from the measured voltage. Our measurements were made using 20 MHz traveling waves with an inverse radian frequency of 8 ns. Traps slower than this do not affect the measurement. This technique should be a useful complement to the transient charge technique.

INTRODUCTION

A fundamental parameter in characterizing electronic transport is the mobility, μ, of the carriers. The Hall effect is widely used to measure μ in crystalline semiconductors; however, such measurements are difficult to interpret in disordered materials when the carrier mean free path is so reduced by disorder as to be comparable to the interatomic spacing.[1] In such materials, the transient charge technique (TCT) is used to perform a direct time-of-flight measurement of carrier mobility; the transit time of a pulse of injected carriers moving in an external dc field is observed giving a measure of the carrier drift mobility.[2,3] In this paper we will report a new method to measure low carrier mobilities in amorphous thin films, using a traveling wave excitation.

It has been pointed out in connection with TCT measurements that, due to trapping effects, there is often a significant differ-

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rence between the effective drift mobility, μ_D, of excess carriers and the free carrier drift mobility, μ_C. Under usual experimental conditions, the TCT measures μ_D. To our knowledge there is no experimental technique to measure μ_C. The measurement technique to be described here uses traveling wave electric fields produced by a surface acoustic wave in a neighboring piezoelectric medium; the effect of traps on the measured mobility depends on the traveling wave frequency used. At usual ultrasonic frequencies (we used 20 MHz) the inverse radian frequency is ~ 10 ns. The measured mobility is not affected by the slower traps.

TRAVELING WAVE MEASUREMENT TECHNIQUE

The traveling wave measurement technique that we propose to use is based on the acoustoelectric effect.[4] This effect is due to the drift of charge carriers caused by the traveling electric field associated with an acoustic wave. The essential feature of this technique is the traveling wave electric field rather than the acoustic wave. For this reason we call it the traveling wave technique rather than the acoustoelectric technique. Measurements of electronic properties in high mobility electronic semiconductors based on the acoustoelectric effect have been reported previously.[5-7] However, to our knowledge, such measurements in low mobility materials have not been performed before. The test film is placed in proximity with surface acoustic waves propagating on an insulating piezoelectric substrate (Fig. 1). The carrier drift is observed as a dc current in the external circuit, given by

$$J_{AE} = qn \frac{(\mu E)^2}{v_s} \quad (1)$$

where J_{AE} is the dc current density caused by the traveling wave
n is the carrier density
μ is the mobility of carriers
E is the rms. traveling wave electric field in the film
v_s is the velocity of the wave
and q is the electronic charge.

Diffusion effects are neglected.

Equation (1) may be derived from a rather simple argument. For simplicity, let us consider a traveling square (rather than sinusoidal) wave. The electron thus finds itself in an electric field E that periodically reverses polarity. The electron velocity is μE during the time it is in the positive field, and $-\mu E$ when it is in the negative field. This would seem to give it zero average velocity; however, it spends more time moving with the wave than moving against the wave. Quantitatively, it has a velocity μE for a length

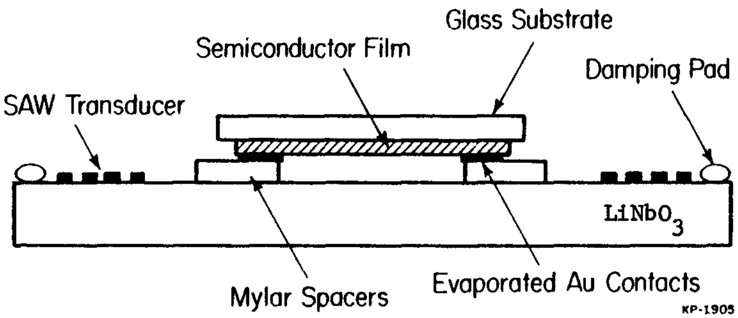

Figure 1: Experimental setup for acoustoelectric mobility measurement.

of time proportional to $1/(v_s - \mu E)$ and a velocity $-\mu E$ for a length of time proportional to $1/(v_s + \mu E)$. It thus has an average velocity $\langle v \rangle$ given by

$$\langle v \rangle = \mu E \cdot \frac{\dfrac{1}{v_s - \mu E} - \dfrac{1}{v_s + \mu E}}{\dfrac{1}{v_s - \mu E} + \dfrac{1}{v_s + \mu E}}$$

$$= (\mu E)^2 / v_s \qquad (2)$$

This produces a dc current density $J_{AE} = (qn\langle v \rangle)$ in agreement with Eq.(1). A more rigorous analysis based on the bunching of carriers by a traveling electric field gives the same result.[4]

It will be noted that J_{AE} is proportional to $n\mu^2$ whereas the current due to dc fields is proportional to $n\mu$. It is thus possible to obtain μ from these two measurements. To avoid contact effects, we usually measure the bucking dc field E_{AE} needed to null out the current due to the traveling wave:

$$E_{AE} = J_{AE}/qn\mu = \mu \cdot \frac{E^2}{v_s} \qquad (3)$$

Knowing E and v_s, we can obtain μ by measuring E_{AE}.

TRAPPING EFFECTS

Now we come to the interesting question of whether the measured mobility is μ_C or μ_D. The answer depends on the frequency of the traveling wave. At high frequencies the traps cannot participate and one measures the free carrier mobility μ_C. At low frequencies the traps can fully equilibrate with the mobile electrons and one measures the effective drift mobility μ_D. To put it quantitatively, let us consider a single trap level with a capture time τ_C (average time an electron remains free) and a release time τ_r (average time an electron remains trapped). It has been shown[8] that the measured mobility μ is given by

$$\mu = \mu_C \cdot \frac{f_o + \omega^2\tau^2}{1 + \omega^2\tau^2} \tag{4}$$

where ω is the radian frequency

$\tau = \tau_C\tau_r/(\tau_C + \tau_r)$

$f_o = \mu_D/\mu_C = \tau_C/(\tau_C + \tau_r)$

At low frequencies ($\omega\tau \ll f_o^{1/2}$),

$$\mu = \mu_D \tag{5a}$$

At high frequencies ($\omega\tau \gg 1$),

$$\mu = \mu_C \tag{5b}$$

At intermediate frequencies ($f_o^{1/2} < \omega\tau < 1$) the measured mobility increases with frequency. It will be noted that there is a close parallel with the TCT measurements, the role of the transit time being played by the inverse radian frequency $1/\omega$. However, while it is difficult to make measurements with short τ_t, it is fairly straightforward to use ultrasonic waves with frequencies in this range. In our first experiment we used a wave frequency of 20 MHz corresponding to $1/\omega \sim 8$ ns; so that the effects of all slower traps were excluded from the measurement.

MEASUREMENT SENSITIVITY

The acoustoelectric current (and hence the bucking d.c. field E_{AE}) reverses direction if the direction of wave propagation is reversed. This property can be used to separate it out from any spurious voltages due to thermal gradients or other causes.

Measuring the bucking d.c. field E_{AE} mentioned previously involves nulling the d.c. current. The accuracy of this measurement depends on how small a fraction of the short-circuit d.c. current can be detected. Therefore measurement sensitivity depends strongly on the magnitude of this current. It can be shown that

$$I \propto \frac{\mu}{R_\square}$$

where $R_\square$ is the sheet resistivity of the film.

Our experiments[9] were performed using 145 mW of acoustic power at a frequency of 20 MHz. The amorphous silicon samples were about 5 mm x 5 mm in size. A sample with $R_\square = 3.2 \times 10^9$ Ω/square produced a current of 38 pA; this yields a mobility of .5 cm^2/V-sec. The Hall mobility measured with similar samples at the RCA Laboratories is about .1 cm^2/V-sec. A second sample with $R_\square = 1.1 \times 10^8$ Ω/square produced a current of 177 pA, implying mobility of .08 cm^2/V-sec. The limit on how low a mobility can be measured depends on the sheet resistance. At 20 MHz with 400 mW of acoustic power, a mobility of .001 cm^2/V-sec in a material with 10^{10} Ω/square would give about 1 pA of current which can be measured with commercially available ammeters.

CONCLUSIONS

A traveling wave technique (TWT) for measuring low carrier mobilities in thin highly resistive amorphous films has been described. The traveling wave electric field is produced by ultrasonic waves generated in a nearby piezoelectric medium. The measurement is made under null current conditions so that contact effects are minimal.

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