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Field-effect measurements of carrier mobilities in transparent conducting films of amorphous indium oxide

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Abstract. We report measurements of carrier mobilities in thin transparent films of amorphous indium oxide using the field effect. The field-effect mobilities (of order 10^{-3} m^2 V^{-1} s^{-1}) are similar to those calculated from conductivity and Hall effect measurements. Their similarity sets an upper limit of order 3×10^{16} m^{-2} to the density of surface-trapped charges. The mobilities are temperature independent, consistent with being determined by ionized donor scattering which is known to dominate in these systems. We show that conduction can be turned on in a device prepared on the insulator side of the metal–insulator transition with mobilities near threshold about an order of magnitude smaller than those observed at higher carrier densities. The difference is attributed to reduced screening. Failure to invert the channel suggests a significant density of traps in addition to the oxygen vacancy donors.

1. Introduction

Transparent, conducting thin films of amorphous indium oxide may be prepared on room-temperature substrates by ion-beam sputtering from an indium target in the presence of oxygen. The technique allows control of composition and films may be prepared from pure metal to fully stoichiometric In_2O_3. The conducting films are formed close to the stoichiometric composition as a result of the presence of oxygen vacancies which act as donors, although only about one in ten appears to be active (Bellingham *et al* 1991b). The transparency results from a band gap in the ultra-violet (between 3.5 and 4 eV) together with a plasma edge from the free electrons in the infra-red. In the range of useful compositions, the electron gas is degenerate and conductivities are of order 10^5 Ω^{-1}m^{-1}. The system is also of interest because it undergoes a metal to insulator transition as the number of carriers is reduced. On the metallic side, weak-localization effects have been identified (Bellingham *et al* 1991a) and on the insulating side, variable-range hopping is observed (Graham *et al* 1992).

Our detailed studies in the transparent conducting range of compositions show that electron mobility is limited primarily by scattering from the ionized donors, the oxygen vacancies (Bellingham *et al* 1990, 1991c). The disorder does not scatter significantly because its spatial scale is much smaller than the electron wavelength. As a result, mobilities are relatively high (of order 5×10^{-3} m^2 V^{-1} s^{-1}). In fact, in the best films, conductivities come close to the limit calculated assuming that impurity scattering is the only important scattering mechanism (Bellingham *et al* 1992).

Normally, mobilities are calculated from the conductivity σ and the Hall coefficient R_H:

$$\mu_H = \sigma R_H.$$

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A direct measurement of mobility is also possible if the material is incorporated in an insulated-gate field-effect transistor structure so that carrier concentration may be changed electrostatically by varying the potential of a neighbouring gate electrode. In this case, a change of gate potential ΔV_g induces a change $\Delta n^{(2)}$ in the two-dimensional carrier density (i.e. in the number of carriers *per unit area*) given by

$$\Delta n^{(2)} = C\Delta V_g/e$$

where C is the capacitance per unit area between gate and film. This results in a change in the conductance G of the channel

$$\Delta G = \mu_{\mathrm{FE}}\Delta n^{(2)} ew/\ell$$

where μ_{FE} is the field-effect mobility, and w the width and ℓ the length of the conducting channel. Then

$$\mu_{\mathrm{FE}} = (\Delta G/\Delta V_g)(\ell/Cw).$$

Such measurements are of interest for two reasons. Firstly, they provide an independent measure of mobility. Secondly, since induced carriers are confined within a screening length of the interface between the film and the gate insulator, measurement of their mobility can in principle give information about conditions near the interface. For example, if surface roughness were important or if there were a large number of trapped charges at the interface, the mobilities of induced carriers would be much less than those of carriers deeper in the film. To our knowledge, modulation by the field effect of the conductivity in transparent conducting films has not previously been reported.

2. Experimental details

The indium oxide films, normally 50 nm thick for the field-effect measurements, were deposited on room-temperature substrates by ion-beam sputtering. Typical deposition conditions were 0.1 nm s^{-1} in an ambient atmosphere of 6×10^{-4} mb of oxygen and 1×10^{-4} mb of argon. Composition was changed by varying the deposition rate or oxygen partial pressure. Films were deposited through masks in the form of a strip with side-arms to allow four-terminal resistance and Hall measurements. Connections were made with silver dag. In fact, there are no contact problems with indium oxide and most resistance measurements for the field effect were made two-terminally using DC techniques. Generally, two samples were made in each deposition, one on glass for conventional transport measurements and one on special substrates for the field-effect structures.

Substrates for the field-effect measurements were sheets of tantalum, chemically polished and anodized to produce a high-quality oxide. The sheet was used as the gate and the oxide acted as the gate insulator. Anodization was typically carried to 100 V to give an oxide thickness of about 170 nm. With the (room-temperature) relative permittivity of 27 this gave a capacitance of about 1.4 mF m^{-2}. Potentials that could be applied between the gate and channel were much less than the anodizing voltage because of concentration of field near the edges of conductors. Measurements to $V_g = 20$ V were normally safe. Also, significant reverse polarities could not be applied at room temperature because of breakdown of the oxide. However, the ease with which high-quality oxides of different thicknesses can be obtained with the anodization technique makes it well suited for experiments of this sort.

3. Experimental results and discussion

The conventional transport measurements gave results consistent with the normal behaviour of this class of materials for which, typically, over the range of carrier concentrations from 10^{25} m^{-3} to 10^{27} m^{-3}, conductivities rise from 5×10^3 $\Omega^{-1}m^{-1}$ to 5×10^5 $\Omega^{-1}m^{-1}$ corresponding to mobilities of order 3×10^{-3} m^2 V^{-1} s^{-1}. We have shown in earlier papers that mobility in the best films is limited by impurity scattering from the ionized donors (Bellingham *et al* 1992). Measured mobilities are similar to those found in silicon at comparable donor densities (e.g., in silicon, $\mu \approx 10^{-2}$ m^2 V^{-1} s^{-1} at $N_d = 10^{25}$ m^{-3}; see Sze 1981).

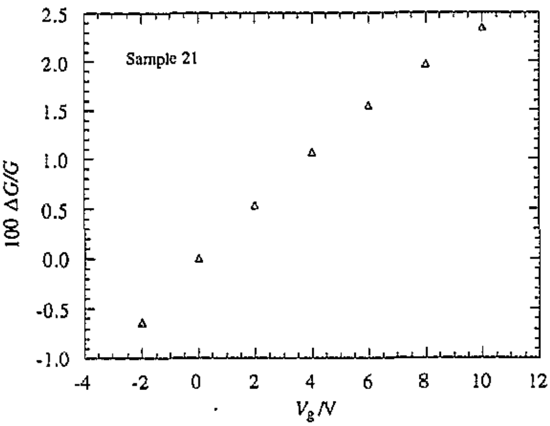

Figure 1. The field effect in a thin film of amorphous indium oxide. The plot shows the fractional change of conductivity as a function of gate bias.

The field-effect measurements showed channel conductances varying approximately linearly with gate potential, a positive V_g increasing the conductivity as would be expected from the n-type nature of the material. A typical example is shown in figure 1. The slight curvature suggests that the mobility of the induced carriers falls as their concentration increases.

Measurements at different temperatures (figure 2) show the transconductance ($\Delta G/\Delta V_g$) falling with reduction of temperature, but the observed variation is fully accounted for by the fall of the relative permittivity of the anodic tantalum oxide. This decreases from 27 at room temperature to 19.5 at 77 K, thereafter becoming essentially independent of temperature. The measurements are therefore consistent with a mobility that is essentially temperature independent. This is what is expected for ionized impurity scattering of a degenerate Fermi gas.

Table 1.

No	n/m^{-3}	σ/Ω^{-1} m^{-1}	μ_{trans}/m^2 V^{-1} s^{-1}	μ_{FE}/m^2 V^{-1} s^{-1}
21	5.9×10^{24}	1.7×10^3	1.8×10^{-3}	1.5×10^{-3}
22	2.0×10^{25}	5.8×10^3	1.8×10^{-3}	3.4×10^{-3}
19	2.7×10^{26}	6.2×10^4	1.4×10^{-3}	7.9×10^{-4}
18	4.0×10^{26}	5.3×10^4	8.6×10^{-4}	7.8×10^{-4}
23	4.7×10^{26}	7.0×10^4	9.3×10^{-4}	5.3×10^{-4}

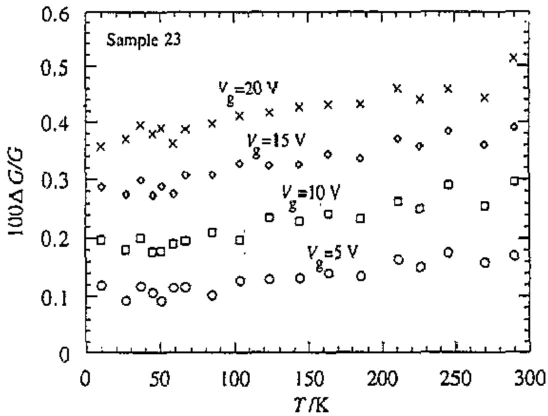

Figure 2. The field effect at various gate voltages as a function of temperature. The variation is entirely accounted for by the temperature dependence of the relative permittivity of the gate insulator: the carrier mobility is essentially independent of temperature.

Numerical results are given for several samples in table 1. It should be noted that the two values of mobility cannot be compared in detail because the measurements were made on different specimens (deposited at the same time) and at different times (the films showed some ageing). Nevertheless, there is some suggestion, disregarding the one exception, that field-effect mobilities may be slightly smaller than Hall mobilities. However, it is clear that there is no evidence for grossly reduced mobility of the induced carriers.

In this respect, it is relevant to estimate the screening length. Using free-electron theory with $m^*/m_e = 0.3$ (Szczyrbowski *et al* 1986) and $\epsilon_r = 9$ (Hamberg and Granquist 1986) the calculated screening length varies from 1.6 to 0.8 nm over the range of carrier concentrations shown in table 1. Induced charges are therefore confined within a few atomic layers of the interface, so it is noteworthy that any excess scattering is so small. By comparing with the ionized impurity scattering in the bulk of the film, it follows that interfacial charge densities must be much smaller than 3×10^{16} m^{-2}. Any other forms of disorder at the interface must be short range ($\ll k_F^{-1} \approx 1$ nm) since they also fail to cause significant excess scattering. It should be remembered that the long electron wavelength is the reason that the intrinsic disorder of the amorphous material does not cause scattering in the bulk.

We also prepared a sample on the insulator side of the metal–insulator transition and were able to turn the channel 'on' by application of a positive gate potential. The results, shown in figure 3, were taken at 77 K to suppress leakage in the oxide and to stabilize it against application of reverse bias. The mobility near threshold, estimated from the gradient in the conducting region, is about 10^{-4} m^2 V^{-1} s^{-1}, approximately an order of magnitude smaller than the values found in the metallic régime. This is an interesting result. In this situation the induced charge is not confined to within a Fermi–Thomas screening length of the surface because there is no degenerate Fermi gas of electrons; instead, it is trapped in a self-consistent potential well at the surface (as in a semiconductor inversion layer). The width of this well depends on factors (like the contact potential) which are unknown in the present structure. However, if we assume that band bending behind the conducting layer is unimportant, then the spatial distribution of the induced charge will only involve the low density of states near the band (mobility) edge, and the charge will be less strongly confined to the interface than in the metallic samples. The reduced mobility cannot therefore be attributed to increased proximity of the induced charge to the interface. The obvious

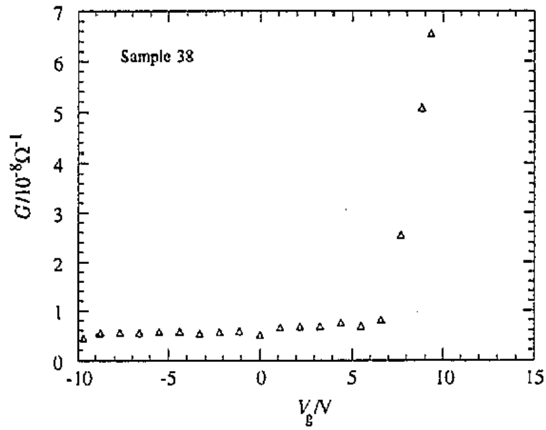

Figure 3. The field effect in a sample that was on the insulating side of the metal–insulator transition in the absence of gate bias.

explanation for the reduced mobility is increased scattering due to the loss of screening by the degenerate electron gas present in the metallic samples.

It should be noted that we failed to invert the channel by application of $V_g = -10$ V, that is, 16 V below the turn-off of the n-type conduction. Since the band gap of indium oxide is only about 3.5 eV, this implies the presence of a significant density of band-gap states. Both surface and bulk localized states may contribute. If the charge is entirely absorbed by interface traps, then the mean density must be greater than 3×10^{16} m^{-2} eV^{-1} which is about an order of magnitude greater than the typical density found at Si–SiO_2 interfaces (Sze 1981). The most likely bulk states to be involved are the donor centres. The Mott criterion (Mott 1990) gives the critical concentration of donors to achieve metallic conduction as about 4×10^{24} m^{-3}. There may therefore still be a large number of donors present, even though this sample is insulating. Only about half this density would be required to prevent inversion if no other states were active. However, it is likely that the disordered structure also produces a significant density of band-gap states, so the failure to invert this specimen is not surprising. Further experimental work is required to explore localized states in this system.

4. Summary

We have reported direct measurement using the field effect of carrier mobility in thin amorphous films of indium oxide. Measured mobilities are similar to those calculated from conductivity and Hall data. It is known that, in well-prepared films, mobility is limited by ionized impurity scattering due to the donors, so the results imply that there is no important additional scattering near the surface. This sets a limit of order 3×10^{-16} m^{-2} on the density of surface-trapped charges. Mobilities are shown to be temperature independent as would be expected for degenerate carriers subject to scattering by the ionized donors. Smaller mobilities were found close to the threshold of conduction in a device that was insulating in the absence of gate bias, as would be expected close to the mobility edge. The failure to invert the channel suggests a significant number of localized states in the band gap.

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References

Bellingham J R, Graham M, Adkins C J and Phillips W A 1991a *J. Non-Cryst. Solids* **137+138** 519
Bellingham J R, Mackenzie A P and Phillips W A 1991b *Appl. Phys. Lett.* **58** 2506
Bellingham J R, Phillips W A and Adkins C J 1990 *J. Phys.: Condens. Matter* **2** 6207
—— 1991c *Thin Solid Films* **195** 23
—— 1992 *J. Mater. Sci. Lett.* **11** 263
Graham M R, Bellingham J R and Adkins C J 1992 *Phil. Mag.* B **65** 669
Hamberg I and Granquist C G 1986 *J. Appl. Phys.* **60** R123
Mott N F 1990 *Metal–Insulator Transitions* (London: Taylor and Francis)
Szczyrbowski J, Scmalzbauer K and Hoffmann H 1986 *Thin Solid Films* **137** 169
Sze S M 1981 *Physics of Semiconductor Devices* (New York: Wiley)