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Amorphous semiconductor mobility limits

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ABSTRACT

A physics-based model for electron and hole mobility in an amorphous semiconductor is developed to estimate the mobility limits of an amorphous semiconductor. The model involves band tail state trapping of a diffusive (Brownian motion) mobility and accounts for both drift- and diffusion-induced transport, as normally encountered in the operation of a thin-film transistor. Employing this model leads to a predicted maximum mobility of ~70 $cm^2V^{-1}s^{-1}$ (~10 $cm^2V^{-1}s^{-1}$) for electrons (holes).

1. Introduction

Amorphous oxide semiconductors (AOS) and amorphous indium gallium zinc oxide (a-IGZO) in particular have recently attracted the attention of the scientific and technological community as a possible replacement for hydrogenated amorphous silicon (a-Si:H) in flat-panel display backplane applications. A key advantage of a-IGZO is its higher electron mobility, $\mu \approx 10\text{-}25$ $cm^2V^{-1}s^{-1}$, compared to ~1 $cm^2V^{-1}s^{-1}$ for a-Si:H. This makes a-IGZO a prime candidate to meet current and near-term display backplane requirements. With the advancement of 4 K and 8 K resolution displays it is likely that the mobility requirements will increase in the future. Hence, there is a strong interest in identifying an AOS with even higher mobility.

Numerous reports [1–5] of AOS or nanocrystalline thin-film transistors (TFTs) with extraordinarily high mobility ($\mu \approx 100\text{-}300$ $cm^2V^{-1}s^{-1}$) are likely unreliable, in our opinion, since they fail to properly account for measurement artifacts, e.g., leaky gate insulator, fringing current due to the use of an unpatterned channel, strongly depletion mode behavior, or underestimation of the gate insulator capacitance [6–8]. The intent of the work presented herein is to formulate a physics-based transport model in order to estimate an upper limit of mobility for n- and p-type amorphous semiconductors. The following development is for an n-type amorphous semiconductor.

2. Model development

The drift mobility of an n-type amorphous semiconductor is often written as, [9–12]

$$\mu_{\text{drift}} = \left(\frac{n}{n+n_T}\right)\mu_0, \tag{1}$$

where n is the free electron concentration, n_T is the trapped electron concentration, and μ_0 is the trap-free drift mobility. If μ_0 is envisaged as a diffusive mobility in which "*It would be more accurate to describe the carriers as almost continuously under the influence of the scattering centers so that their motion would be more like Brownian motion than wave propagation.*" [13] then μ_0 may be expressed as, [10–12]

$$\mu_0 = \frac{q\hbar}{6m_e^* k_B T}, \tag{2}$$

where q is the elementary charge, $\hbar$ is the reduced Planck constant, k_B is the Boltzmann constant, m_e^* is the electron effective mass, and T is the temperature. Note that due to the complicated nature of electron motion near the mobility edge Eq. (2) is only valid for transport near room temperature (T = 300 K). The free and trapped electron concentrations are given by,

$$n = \int_{E_C}^{\infty} g_C(E) f(E) dE, \tag{3}$$

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and

$$n_T = \int_{E_V}^{E_C} g_{TA}(E) f(E) dE, \tag{4}$$

respectively, where E_C and E_V are the conduction and valence band mobility edges, respectively, g_{TA} is the conduction band tail density of states and f is the Fermi–Dirac occupancy function. Typically, an amorphous semiconductor is characterized by an exponential trap tail state density [10–12]. The acceptor-like conduction band tail state distribution is equal to [14]

$$g_{TA}(E) = N_{TA} \exp\left(\frac{E - E_C}{W_{TA}}\right), \tag{5}$$

with

$$N_{TA} = \frac{1}{2\pi^2}\left(\frac{2m_e^*}{\hbar^2}\right)^{\frac{3}{2}}, \tag{6}$$

where $N_{TA} = g_{TA}(E_C)$ is the peak density of acceptor-like conduction band tail states evaluated at the mobility edge, E_C, and W_{TA} is the conduction band Urbach energy characterizing the exponential decrease in the density of conduction band tail states below the conduction band mobility edge. The conduction band density of states (DOS) is given as,

$$g_C(E) = \frac{1}{2\pi^2}\left(\frac{2m_e^*}{\hbar^2}\right)^{\frac{3}{2}}\left(1 + \sqrt{E - E_C}\right), \tag{7}$$

where $g_C(E)$ is modified from the standard textbook crystalline case, e.g., Blakemore [15], in order to ensure a continuous DOS exists at the mobility edge.

The μ_{drift} expression given in Eq. (1) is appropriate for describing electron conduction in the accumulation layer of a TFT operating at a gate voltage above threshold, where the channel current is dominated by drift, but is not appropriate at sub-threshold gate voltages since diffusion dominates [14]. Thus, by introducing a diffusion mobility given by,

$$\mu_{\text{diff}} = \mu_{\text{drift}} \frac{n}{N_C}, \tag{8}$$

where N_C is the conduction band effective density of states,

$$N_C = 2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{\frac{3}{2}}, \tag{9}$$

the amorphous semiconductor electron mobility arising from drift and/or diffusion is equal to

$$\mu^{-1} = \mu_{\text{drift}}^{-1} + \mu_{\text{diff}}^{-1}. \tag{10}$$

Eqs. (1)–(10) constitute our n-type amorphous semiconductor mobility transport model. An analogous set of equations involving p, p_T, m_h^*, E_V, g_{TD}, N_{TD}, W_{TD}, and N_V may be developed to describe hole transport in a p-type amorphous semiconductor, where the subscript TD denotes an exponential distribution of donor-like valence band tail states [14].

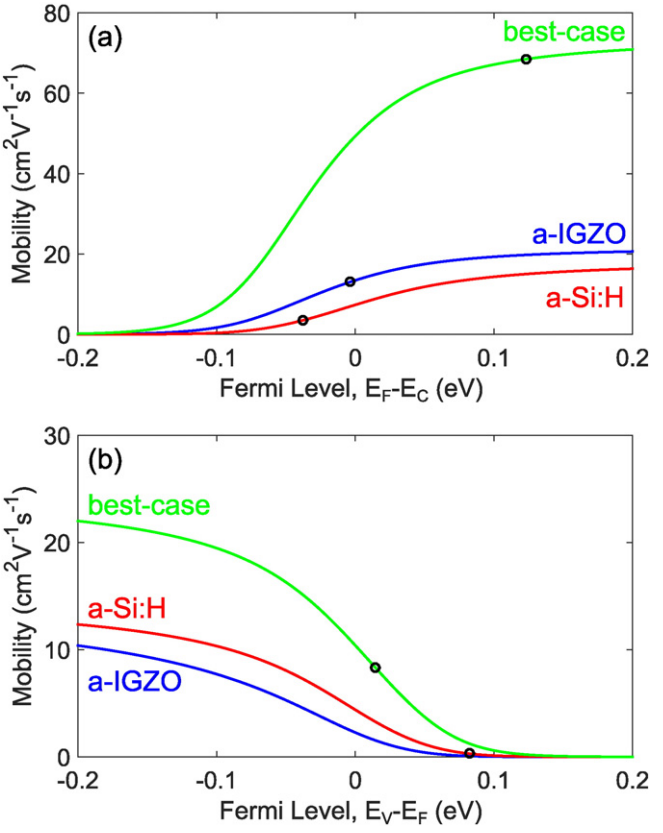

Fig. 1. Amorphous semiconductor mobility μ as a function of Fermi level position for (a) electrons and (b) holes.

3. Results and discussion

Eqs. (1)–(10) and their hole transport analogs are employed to generate plots of the mobility as a function of Fermi level position for three amorphous semiconductors — a-Si:H, a-IGZO, and a best-case amorphous semiconductor that is our estimate of the upper limit of amorphous semiconductor mobility — for both electrons (Fig. 1a) and holes (Fig. 1b). No analytical expressions for the integration of Eqs. (3) and (4) exist, hence, a mathematical software package was used to solve Eqs. (3) and (4) numerically. Note that these amorphous semiconductor transport curves are determined by specifying only the temperature, $T = 300$ K, and two material parameters, m_e^* and W_{TA} for electrons, or m_h^* and W_{TD} for holes. Effective masses and Urbach energies employed to generate the curves shown in Fig. 1 are collected in Table 1. First consider the electron transport trends shown in Fig. 1a. It is clear that the electron mobility of a-IGZO is improved compared to that of a-Si:H, as is well established. For a well-informed reader, however, a puzzling aspect of Fig. 1a is the anomalously large mobility of ~15 $cm^2V^{-1}s^{-1}$ for a-Si:H. TFT channel mobility for a-Si:H is typically ~1 $cm^2V^{-1}s^{-1}$. This puzzle is resolved by referring to Eq. (1) and recognizing that amorphous semiconductor mobility is degraded from that of its maximum diffusive mobility (μ_0) by trapping. The maximum in mobility shown in Fig. 1a can only be obtained if the Fermi level can be pushed 0.2 eV above the mobility edge. The extent to which the Fermi level can be modulated towards or beyond the mobility edge is determined by band tail trapping.

The total band tail trap density, n_{total}, plays a key role in establishing amorphous semiconductor transport. For electron transport, n_{total} is equal to

$$n_{\text{total}} = \int_{E_V}^{E_C} g_{TA}(E) dE = N_{TA} W_{TA}. \tag{11}$$