Electronic Conduction Mechanisms in Insulators

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Abstract—The current density–electric field ($J - \xi$) characteristics of four insulators of dramatically different electrical qualities are assessed in terms of their operative electronic conduction mechanisms. Conduction in the two high-quality insulators is dominated by Ohmic conduction and Fowler–Nordheim tunneling, whereas conduction in the two low-quality insulators involves Ohmic conduction and space-charge limited current (SCLC). Ohmic conduction and SCLC are somewhat puzzling mechanisms for contributing to insulator leakage current since they require the existence of an Ohmic contact at the cathode. Our conventional understanding of an Ohmic contact makes it difficult to ascertain how an Ohmic contact could be formed to a wide bandgap insulator. This Ohmic contact dilemma is resolved by formulating an equivalent circuit appropriate for ascertaining the $J - \xi$ characteristics of an insulator and then recognizing that an insulator Ohmic contact is obtained when the injection-limited current density from the cathode electrode is greater than that of the operative bulk-limited current density, i.e., Ohmic or SCLC for the four insulators under consideration.

Index Terms—Bulk-limited conduction, injection-limited conduction, insulator, leakage current, Ohmic contact.

I. INTRODUCTION

Since very few electrons are present in the conduction band of an insulator in equilibrium, electrons usually must be supplied from a cathode contact in order for an appreciable leakage current to flow through the insulator. (In this contribution, electron transport is assumed to dominate so that hole transport can be ignored.) Leakage current due to this type of electronic transport is referred to as injection-limited conduction. As listed in Table I and illustrated in Fig. 1, electron injection can be accomplished over a barrier (thermionic emission), through a barrier (Fowler–Nordheim tunneling), or a combination of thermal excitation and subsequent tunneling through a thinner barrier (thermionic-field emission).

Given this, it is very puzzling that steady-state electrical assessment of real insulators often leads to the conclusion that bulk-limited conduction (see Table I) is an important or even a dominant contribution to leakage current. This is astonishing

TABLE I

CLASSIFICATION OF COMMON INSULATOR ELECTRONIC CONDUCTION MECHANISMS

| Bulk-Limited                  | Injection-Limited          |
|-------------------------------|-----------------------------|
| Ohmic                         | Thermionic emission         |
| Space-charge limited current  | Fowler-Nordheim tunneling   |
| Frenkel-Poole emission        | Thermionic-field emission   |

Fig. 1. Energy band diagram representation of electronic injection-limited conduction mechanisms: thermionic emission, thermionic-field emission, and Fowler–Nordheim tunneling.

since Ohmic and space-charge limited current (SCLC) require that the cathode contact be Ohmic while Frenkel–Poole (FP) emission, i.e., conduction arising from the thermal emission of traps lying below the conduction band minimum, can only be sustained in a steady-state manner if the cathode functions as an Ohmic-like contact so that FP traps may be continuously refilled after emission [1]. Thus, the following question arises: How is an Ohmic or Ohmic-like contact formed to an insulator?

The objective of this contribution is to offer a framework for assessing leakage current behavior in insulators. We accomplish this by first formulating analytical expressions for electronic conduction mechanisms commonly observed in insulators. Then, we examine the electrical properties of four insulators of dramatically differing electrical quality. Conduction mechanisms are identified for each insulator and their measured electrical characteristics are accurately simulated using an appropriate analytical expression for each conduction mechanism. Subsequently, an insulator equivalent circuit is formulated in order to serve as a basis for development of a simulator, which can, in principle, account for all six of the bulk- or injection-limited conduction mechanisms under consideration (Table I). Finally, the nature of an Ohmic contact to a wide bandgap insulator is elucidated.

II. EXPERIMENTAL DETAILS

Metal-insulator–metal (MIM) test devices were fabricated using degenerately doped p-type (p⁺) Si as the bottom ‘metal’ contact. Insulators were formed on top of the p⁺-Si substrate
using the following deposition methods. The 100 nm of SiO$_2$ was grown via thermal oxidation. The 10 and 64 nm of Al$_2$O$_3$ was deposited by plasma-enhanced atomic layer deposition (PEALD) and solution deposition (SD), respectively. The 98 nm of lanthanum zirconium oxide (LZO) was deposited by SD. PEALD (SD) Al$_2$O$_3$ and SD LZO films were subjected to a post-deposition anneal at 400 (500) °C in air for 1 h. Aluminum contacts with 500-μm diameter were deposited on top of each insulator via thermal evaporation and patterned via a shadow mask. MIM devices were completed by etching through each insulator and making contact to the underlying p$^+$-Si substrate using indium solder. MIM devices were electrically characterized using an Agilent 4155C semiconductor parameter analyzer in the dark at room temperature. All electrical testing was accomplished using the Al top metal as a cathode. Insulator thicknesses were confirmed using ellipsometry.

III. $J - \xi$ MODELING

Table II summarizes the analytical equations describing steady-state current density–electric field ($J - \xi$) behavior for all six bulk- and injection-limited electronic conduction mechanisms found in Table I. The parentheses notation used in Table II specifies model parameters and (separated by a semicolon) temperature (when appropriate), the only physical operating parameter of relevance in this simulation. For example, the Ohmic conduction current density, $J_{\Omega}(m^*_e, n_0; T)$, reveals that the model parameters are the effective mass, $m^*_e$, and the equilibrium free electron concentration, $n_0$, while the physical operating parameter temperature $T$ is implicitly relevant since it is used to model the mobility $\mu$ as discussed below.

In our formulation, calculation of all of the six conduction mechanisms requires specifying seven model parameters, i.e., electron effective mass, $m^*_e$; equilibrium free electron concentration, $n_0$; low-frequency (static) dielectric constant, $\epsilon_s$; high-frequency (optical) dielectric constant, $\epsilon_{\infty}$; acceptor-like conduction band tail state characteristic (Urbach) energy, $W_{\Omega}$; trap energy, $q\phi_T$; and cathode metal-insulator barrier energy, $q\phi_B$; as well as the physical operating parameter temperature, $T$. Several terms used in the current density expressions shown in the top of Table II are defined as auxiliary parameters, as shown in the middle of Table II, i.e., electron mobility, $\mu$; conduction band effective density of states, $N_C$; peak density of acceptor-like conduction band tail states, $N_{\Omega}$; effective Richardson constant, $A^*$; and barrier lowering due to the Schottky, $\Delta E$, or the FP effect, $\Delta E_{FP}$. Displacement current, $J_{DPL}$, can be misinterpreted as a dc current, but is actually a transient effect. $J_{DPL}$ is dependent on the insulator capacitance density, $C_I = \epsilon_s / h$ (F cm$^{-2}$), and the voltage ramp rate, $(dV/dt)$ (V s$^{-1}$), where $h$ is the insulator thickness (cm). When measuring a leakage current density of less than $10^{-8}$ A cm$^{-2}$ at low electric fields of less than 2 MV/cm, a voltage ramp rate of less than 10 mV s$^{-1}$ is recommended in order to minimize displacement current artifacts [2]. Note that we model $\mu$ as a diffusive mobility, as exemplified by Brownian motion, in accordance with the amorphous nature of a practical insulator [3]–[5]. The auxiliary parameter for $N_{\Omega}$ is new. It is derived by setting the slope of the band tail state density ($d\xi_{\Omega}/dE$) equal to the slope of the conduction band density of states ($d\xi_C/dE$) at the mobility edge in order to ensure that the density of states is continuous at the mobility edge [6]. The equation used to describe SCLC in Table II pertains to SCLC involving an exponential trap distribution; this type of trap distribution is relevant to the case of band tail states associated with an amorphous insulator [1], [3]–[6]. Series resistance, $R_S$ ($\Omega$ cm$^2$), is included in the SCLC equation of Table II.

All nine model parameters (including $R_S$) are listed at the bottom of Table II. The first five are used to simulate the measured $J - \xi$ characteristics of thermal SiO$_2$, PEALD Al$_2$O$_3$, SD Al$_2$O$_3$, and SD LZO. In our simulation, $\epsilon_s$ and $m^*_e$ (color-coded blue) are fixed values obtained from the literature, while $n_0$, $q\phi_B$, $W_{\Omega}$, and $R_S$ (color-coded green) are varied to optimize simulated $J - \xi$ curves in order to obtain a best fit to the measured data. Contact area variation due to shadow mask processing and thickness nonuniformity across the substrate accounts for minor variations in estimated $n_0$ and $q\phi_B$ values. $\epsilon_{\infty}$ and $q\phi_T$ are not declared in the simulation since thermionic-field emission and FP emission do not appear to appreciably contribute to the leakage currents of the four insulators under consideration.

IV. EXPERIMENTAL RESULTS

Fig. 2 compares measured and simulated log($J$)–$\xi$ curves for MIM test devices using thermal SiO$_2$, PEALD Al$_2$O$_3$, SD Al$_2$O$_3$, and LZO as an insulator. Thermal SiO$_2$ and PEALD Al$_2$O$_3$ log($J$)–$\xi$ curves exhibit similar behavior in that both have a relatively small current density at electric fields of $0 < \xi < 5 - 6$ MV/cm, and exhibit a knee at a higher field, beyond which the current density increases notably. In contrast, SD Al$_2$O$_3$ and LZO $J - \xi$ curves exhibit significantly more leakage current at lower electric fields of $0 < \xi < 3$ MV/cm. Measured and simulated $J - \xi$ curves
TABLE II
EQUATIONS AND PARAMETERS USED FOR SIMULATION OF INSULATOR CURRENT DENSITY VERSUS ELECTRIC FIELD \((J - \zeta)\) CHARACTERISTICS. MODEL PARAMETERS COLOR-CODED IN BLUE (GREEN) ARE FIXED (VARIED TO OPTIMIZE FIT)

| Conduction Mechanism | Equation |
|----------------------|----------|
| Ohmic                | \(J(O)(n_0, T) = q\mu n_0 \zeta [7]\) |
| SCLC (exponential trap density w/ series resistance) | \(J_{SCLC, exp}(n_0, \zeta, T) = q^{m-1}\mu N_0 \left(\frac{\zeta}{m+1}\right)^{m} \left(\frac{V - J R}{m+1}\right)^{m+1}\) |
| Frenkel-Poole emission | \(J_{FP}(n_0, \zeta, T) = q\mu N_0 \zeta exp(-\frac{2\pi \eta}{k_B T}) [7]\) |
| Thermionic emission | \(J_{TE}(n_0, \zeta, T) = A^T exp(-\frac{\eta}{k_B T}) [7]\) |
| Fowler-Nordheim tunneling | \(J_{FN}(n_0, \zeta, \phi_B) = \frac{\zeta e^2}{4\pi}\left(\frac{\zeta e^2}{3h_0}\right)^{5/2} \left(1 - \left(\frac{\Delta E}{\zeta e^2 k_B T}\right)^{5/3}\right) dz [9, 10]\) |
| Thermionic field emission | \(J_{TE}(n_0, \zeta, \phi_B, \zeta, T) = J_{TE} \int_{0}^{\frac{4v^2 (\zeta e^2 k_B T)^{5/2}}{3h_0}} \left(1 - \left(\frac{\Delta E}{\zeta e^2 k_B T}\right)^{5/3}\right) dz\) |

| Auxiliary Parameters | Equation (Units) |
|----------------------|------------------|
| Displacement current | \(C_{DL} \frac{dV}{dt} (A cm^{-2})\) |
| Electron mobility | \(\mu = \frac{q}{6\pi \varepsilon_0 \varepsilon_{0} k_B T} (cm^2 V^{-1} s^{-1}) [3]-[6]\) |
| Conduction band Urbach energy | \(W_{TA} = mk_B T (meV) [1]\) |
| Total conduction band tail state density | \(n_{TOTAL} = 8.0 \times 10^{21} \left(W_{TA}(eV) \frac{m_B^2}{m_0}\right)^{1} (cm^{-3}) [6]\) |
| Peak conduction band tail state density | \(N_{TA} = 8.0 \times 10^{21} \sqrt{W_{TA}(eV) \frac{m_B^2}{m_0}} \left(\frac{m_B^2}{m_0}\right)^{1/2} (cm^{-3} eV^{-1}) [6]\) |
| Effective Richardson constant | \(A^T = 120 \left(\frac{m_B^2}{m_0}\right) (A cm^{-2} K^{-2}) [11, 12]\) |
| Barrier lowering energy | \(\Delta E = \sqrt{\frac{2\zeta}{4\pi e^2}} \Delta E_{FP} = \sqrt{\frac{2\zeta}{4\pi e^2}} (eV) [11, 12]\) |

| Model Parameters | Symbol (Units) | Insulator |
|------------------|----------------|-----------|
| Low-frequency dielectric constant | \(\varepsilon_s\) | \(\varepsilon_s\) | \(\varepsilon_s\) | \(\varepsilon_s\) | \(\varepsilon_s\) |
| Electron effective mass | \(m_e^*\) | 0.4 [15]-[17] | 0.4 [18] | 0.4 [18] | 0.2 [19], [20] |
| Equilibrium free electron concentration | \(n_0 (cm^{-3})\) | 24 | 550 | 1.65 \times 10^4 | 4.5 \times 10^4 |
| Barrier height | \(q\phi_B (eV)\) | 3.1 | 2.8 | - | - |
| Conduction band Urbach energy | \(W_{TA} (meV)\) | - | 220 | 51 |
| Peak conduction band tail state density | \(N_{TA} (cm^{-3} eV^{-1})\) | - | 9.5 \times 10^{20} | 1.6 \times 10^{20} |
| Series resistance | \(R_S (\Omega - cm^2)\) | - | 400 | - |
| High-frequency dielectric constant | \(\varepsilon_{\infty}\) | - | - | - |
| Trap energy | \(q\phi_T\) | - | - | - |

match quite well over most of the range of applied electric field.

Fig. 3 shows log\((J) - \log(\zeta)\) curves for all four insulators under consideration. When plotted on a log–log scale, it becomes more apparent that there are two dominant regimes of \(J - \zeta\) behavior for each insulator. Fig. 3(a) and (b) indicates that the \(J - \zeta\) behavior in thermal SiO2 and PEALD Al2O3 is dominated by Ohmic and Fowler–Nordheim tunneling conduction mechanisms. In contrast, Fig. 3(c) and 3(d) demonstrates that SD Al2O3 and SD LZO exhibit much larger Ohmic leakage current densities at low fields than thermal SiO2 and PEALD Al2O3 and also suffer from a much earlier onset of an increase in current density due to SCLC.
The SCLC fits \( J - V^{m+1} \) shown in Fig. 3(c) and (d) result in power law exponents of \( m = 8.5 \) and \( m = 2 \), respectively. A value of \( m + 1 > 2 \) is indicative of band tail state trapping [1] [21] [22]. Also, the \( m \) auxiliary equation included in Table II shows that \( m \) is related to the conduction band Urbach energy, \( W_{TA} \). The \( W_{TA}[SD\ Al_2O_3] = 51 \) meV value is relatively large, but is well within the range normally expected for an amorphous insulator. However, the \( W_{TA}[SD\ Al_2O_3] = 220 \) meV value is extraordinarily large. Since the SD Al_2O_3 insulator was deposited in such a manner to intentionally increase its porosity [23], it is likely that its anomalously large Urbach energy is attributable, at least in part, to its porosity. Porous silicon Urbach energies in the range of 150–300 meV have been reported [24]. Peak conduction band tail state density \( N_{TA} \) is calculated from \( W_{TA} \), as shown in Table II. In addition, using the equation for the total conduction band tail state density \( n_{\text{TOTAL}} \) listed in Table II, or recognizing that \( n_{\text{TOTAL}} = N_{TA} W_{TA} \) [6], \( n_{\text{TOTAL}} = 2.0 \times 10^{20} \) cm\(^{-3} \), and \( n_{\text{TOTAL}} = 8.2 \times 10^{18} \) cm\(^{-3} \) for SD Al_2O_3 and SD LZO, respectively. Note that, the \( n_{\text{TOTAL}} \) relationship indicates that an increase in the Urbach energy results in a corresponding increase in the total amount of conduction band disorder which is primarily associated with the cation sublattice [3] [4]. Finally, in Fig. 3(c), the rollover behavior at an electric field greater than \( \sim 2 \) MV/cm is attributed to series resistance, i.e., \( R_S = 400 \ \Omega \cdot \text{cm}^2 \), which is modeled as a parasitic voltage drop, as shown in the equation for exponential SCLC in Table II.

V. EQUIVALENT CIRCUIT CONSIDERATIONS

Fig. 4 is an equivalent circuit model used to simulate insulator \( J - \xi \) curves. Each conduction mechanism is modeled as a voltage-controlled current source since the electric field is assumed to be uniform across the insulator. The total insulator current density \( J \) is given by

\[
J = J_{DPL} + J_{TE} + J_{FN} + J_{TFE} + \frac{J_{IOI}(J_{IOI} + J_{SCLC} + J_{FP})}{J_{IOI} + J_{IOI} + J_{SCLC} + J_{FP}}. \tag{1}
\]

Note that injection-limited current densities, i.e., \( J_{TE}, J_{FN}, \) and \( J_{TFE} \), contribute directly to \( J \). In contrast, bulk-limited current densities, i.e., \( J_{IOI}, J_{SCLC}, \) and \( J_{FP} \), only contribute directly to \( J \) when \( J_{IOI} \gg J_{IOI} + J_{SCLC} + J_{FP} \) so that Eq. 1 simplifies to

\[
J = J_{DPL} + J_{TE} + J_{FN} + J_{TFE} + J_{IOI} + J_{SCLC} + J_{FP}.
\]
In Eq. 1, $J_{OI}$ denotes an Ohmic injection current density, as discussed in Section VI.

Satisfying the less restrictive inequality $J_{OI} > J_{\Omega} + J_{SCLC} + J_{FP}$ corresponds to the cathode contact being able to supply a sufficient amount of current so that the cathode functions as an Ohmic contact. Thus, satisfying the inequality $J_{OI} > J_{\Omega} + J_{SCLC} + J_{FP}$ constitutes our definition of what constitutes an Ohmic contact. This definition of an Ohmic contact is quite different from the normal view in which the cathode metal contact is required to maintain an unlimited concentration of charge carriers [1] [25].

Finally, a capacitor with a capacitance density, $C_I$, is connected in parallel in Fig. 4 in order to account for the displacement current density, $J_{DPL}$, associated with the ramp rate of the applied voltage waveform.

All conduction mechanisms included in Fig. 4 have now been discussed within the context of Table II, except for Ohmic injection, $J_{OI}$, as considered in Section VI. A potential source of confusion is our use of the term “Ohmic” in two different ways: 1) denoting the flow of Ohmic current in the insulator ($J_{\Omega}$) or 2) referring to the injection of electrons from the cathode contact in order that the contact function as an Ohmic contact ($J_{OI}$).

**VI. Nature of an Ohmic Contact to a Wide Bandgap Insulator**

Steady-state bulk-limited conduction is observed for all of the insulators included in Fig. 2. This is surprising since it implies that an Ohmic contact is formed to the insulator at the cathode. Rose asserts that such an Ohmic contact is “an electrode that supplies an excess or a reservoir of carriers ready to enter the insulator as needed” [25]. An energy band diagram illustrating the type of Ohmic contact envisaged by Rose is shown in Fig. 5. In equilibrium, as indicated in Fig. 5(a), electrons at the Fermi level of the metal, $E_F$, see an energy barrier height, $q\phi_B$, between $E_F$ and the conduction band minimum of the insulator, $E_C$. As a negative bias is applied to the cathode metal, the original energy barrier, $q\phi_B$, is reduced due to image force barrier lowering, $\Delta E$. For this virtual cathode to function as an Ohmic contact, it must be capable of supplying a larger current density than that required for bulk-limited conduction due to Ohmic conduction or SCLC, for the insulators considered herein. In turn, the current density that this virtual cathode can supply depends critically on the magnitude of $q\phi_B$. Rose’s picture of an insulator Ohmic contact implies that thermionic emission or thermionic emission with barrier lowering is the operative mechanism responsible for Ohmic injection. In the following, this hypothesis is examined for the case of thermal SiO$_2$ with an Al metal contact, an important test case since its injection barrier is so large, i.e., $q\phi_B = 3.1$ eV.

Fig. 6 is a simulation [at an electric field of 0.3 MV/cm, corresponding to the approximate onset of Ohmic current, as shown in Fig. 3(a)] of the leakage current density expected for thermal SiO$_2$ due to thermionic emission ($J_{TE}$, black solid line) or thermionic emission with barrier lowering ($J_{TE, BL}$, black dotted line). The blue solid line shows the measured Ohmic current density, $J_{\Omega}$, observed for thermal SiO$_2$ at an electric field of 0.3 MV/cm. The green dashed line indicates the approximate, $q\phi_B$, expected for Al-SiO$_2$.
expected barrier, \( q\phi_B(Al - SiO_2) = 3.1 \) eV (green dashed line). Fig. 6 is revealing. It shows that thermionic emission (thermionic emission with barrier lowering) is a viable Ohmic line). Fig. 6 is revealing. It shows that thermionic emission is replaced by two discrete trap states in Fig. 8(a) in order to supply enough electrons to the SiO2 conduction band, \( J_{ST} \), (green) in order to sustain steady-state bulk-limited conduction. Fig. 8(b) shows an equivalent circuit revealing how the Ohmic injection current density, \( J_{OI} \), is determined from the three trap-mediated contributions. From the equivalent circuit shown in Fig. 8(b), it is evident that \( J_{OI} \) is equal to the reciprocal sum of \( J_{TFE,T} \), \( J_{TT} \), and \( J_{ST} \) and is, therefore, dominated by the smallest current density contribution.

Table III lists the equations used to very crudely model, \( J_{TFE,T} \), \( J_{TT} \), and \( J_{ST} \) using a discrete trap approximation. Trap-mediated thermionic-field emission \( J_{TFE,T} \) is modified from the equation for thermionic-field emission given in Table II by incorporating the energy of the deep trap state, \( q\phi_T \), thus accounting for electron tunneling into a trap state, rather than \( E_C \) [9] [10]. The trap-mediated thermionic emission current density, \( J_{TFE,T} \), is similarly formulated. Current density due to electron emission from a deep trap state to a shallow state, \( J_{TT} \), is formulated using (11) from [31], but ignoring hole emission, \( \epsilon_p \), and evaluating electron emission, \( \epsilon_n \), using the expression given on [31], pp. 1620. The filled deep trap density, \( n_{DT} \), and empty shallow trap density, \( p_{ST} \), are crudely estimated to be \( \approx 10^{16} \) cm\(^{-3}\). Also the term \( \exp(-2R/R_0) \) is included in \( J_{TT} \) in order to account for tunneling from a deep trap state to a shallow trap state [29] [30]; \( R \) is the localized state separation distance and \( R_0 \) is the localization length. Note that, the adiabatic limit, i.e., \( \exp(-2R/R_0) \approx 1 \), is assumed in the simulation shown in Fig. 9 in order to circumvent complications associated with estimating \( R \) and \( R_0 \) as well as including high electric field effects, barrier lowering, and polarization corrections [29]. The current density due to electron emission from the shallow trap state to \( E_C \), \( J_{ST} \),
TABLE III

EQUATIONS AND PARAMETERS USED FOR SIMULATION OF OHMIC INJECTION CURRENT
DENSITY CONTRIBUTIONS. MODEL PARAMETERS ARE FOR THERMAL SiO2

| Ohmic Injection Contributions | Equation |
|-------------------------------|----------|
| Trap-mediated thermionic-field emission | \( J_{TFE,T}(m^*_e, \phi_B, \phi_T, \epsilon_{\infty}; T) = J_{TFE,T} \left( \frac{x^3}{4} \right) \frac{1}{z} \exp \left( z - z^{3/2} \right) \ldots \) [9], [10] |
| Trap-to-trap emission | \( J_{TT} = \frac{1}{2} q_v \sigma_n n_{DT} \exp \left( -\frac{\Delta E_{TT}}{k_B T} - \frac{2 \theta}{R_0} \right) \) [28]-[30] |
| Shallow trap emission | \( J_{ST} = \frac{1}{2} q_v \sigma_n n_{ST} N_{C} \exp \left( -\frac{E_{ST}}{k_B T} \right) \) [28] |

| Auxiliary Parameters | Equation (Units) |
|---------------------|-----------------|
| Trap-mediated thermionic emission | \( J_{TFE,T} = A^{*} \gamma_{T}^{2} e \left( \frac{-2(\phi_B - \phi_T) - \Delta E_{T}}{k_B T} \right) (Acm^{-2}) \) |
| Trap-to-trap energy | \( \Delta E_{TT} = E_{DT} - E_{ST} \) (eV) |
| Conduction band effective density of states | \( N_{C} = 2 \left( \frac{m^*_e k_B T}{2\pi h^2} \right)^{3/2} (cm^{-3}) \) [7] |

| Model Parameters | Values |
|------------------|--------|
| Filled shallow trap density | \( n_{ST} \approx 10^{16} \) cm\(^{-3}\) [31] |
| Empty shallow trap density | \( p_{ST} \approx 10^{16} \) cm\(^{-3}\) |
| Filled deep trap density | \( n_{DT} \approx 10^{16} \) cm\(^{-3}\) |
| Conduction band effective density of states | \( N_{C} = 6.3 \times 10^{18} \) cm\(^{-3}\) |
| Electron thermal velocity | \( v_{th} = 10^7 \) cm/s |
| Neutral trap capture cross-section | \( \sigma_n = 10^{-15} \) cm\(^2\) [26] |
| Electric field | \( \xi = 0.3 \) MV/cm |
| Insulator thickness | \( h = 100 \) nm |
| Localized state separation distance | \( \frac{R}{R_0} \exp \left( -2R/R_0 \right) \approx 1 \) (adiabatic limit) |
| Localization length | \( R \) |

is dependent on the depth of the shallow trap, \( E_{ST} \) and the concentration of filled shallow trap states, \( n_{ST} \approx 10^{16} \) cm\(^{-3}\). Both \( J_{TT} \) and \( J_{ST} \) utilize an electron capture cross section for a neutral trap, \( \sigma_n = 10^{-15} \) cm\(^2\), similar to the reported value of \( 10^{-16} \) cm\(^2\) for low-temperature electron emission from a shallow trap [26].

Fig. 9 shows a simulation of the current density as a function of energy for the three Ohmic injection contributions listed in Table III, including the energy for trap-mediated thermionic-field emission, \( (q(\phi_B - \phi_T)) \), trap-to-trap emission, \( (E_{DT} - E_{ST}) \), and emission from a shallow trap to \( E_C \) (\( E_{ST} \)). The measured Ohmic current density for thermal SiO2 at an electric field of 0.3 MV/cm, \( J_{O1}(SiO2) \approx 4 \times 10^{-10} \) A cm\(^{-2}\) (black), is also shown in Fig. 9. Recall that \( J_{O1} > J_{O2}(SiO2) \) is our condition that the cathode metal is properly functioning as an Ohmic contact. Considering each contribution to \( J_{O1} \) separately, Fig. 9 reveals that \( q(\phi_B - \phi_T) \lesssim 0.4 \) eV, \( E_{DT} - E_{ST} \lesssim 0.6 \) eV, and \( E_{ST} \lesssim 0.7 \) eV for the \( J_{TFE,T} \), \( J_{TT} \), and \( J_{ST} \) contribution, respectively, to meet the Ohmic contact requirement. All three of these Ohmic contact requirements are met using the trap distribution for SiO2 given in Fig. 7. Thus, Ohmic injection in Al-SiO2 appears to involve a complicated process of trap-mediated thermionic-field emission, trap-to-trap emission, and trap emission to the SiO2 conduction band to provide enough conduction band electrons to sustain Ohmic current flow.

It is important to re-emphasize that the Ohmic injection model outlined in Table III is very crude and as currently formulated is not capable of quantitatively accounting for the Ohmic injection trends. For example, the adiabatic limit assumption in which \( \exp \left( -2R/R_0 \right) \approx 1 \) implies that \( R \ll R_0 \), which is not true unless \( n_{DT} \) and \( p_{ST} \) are orders of magnitude larger than their assumed value of \( \sim 10^{16} \) cm\(^{-3}\). Thus, the Ohmic injection model of Table III needs to be refined and enhanced by accounting for high electric field effects, barrier lowering, and polarization corrections [29].
VII. Conclusion

The $J - \xi$ characteristics of four insulators are assessed. High-quality insulators (thermal SiO$_2$ and PEALD Al$_2$O$_3$) exhibit low leakage current densities involving Ohmic conduction and Fowler–Nordheim tunneling, whereas low-quality insulators (SD Al$_2$O$_3$ and LZO) exhibit high leakage current densities involving Ohmic conduction and SCLC. Formulation of an equivalent circuit for insulator conduction mechanisms leads to the condition $J_{OII} > J_a + J_{SCLC} + J_{FP}$, which constitutes a new definition of what constitutes an Ohmic contact. When the insulator injection barrier is large, i.e., $\phi \theta > 1$ eV, satisfying the Ohmic contact condition can only be achieved when Ohmic injection is trap-mediated.

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Authors’ photographs and biographies not available at the time of publication.