A model for the high field leakage current in nitrided oxides

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(Received 1 March 2007; accepted 2 April 2007; published online 23 May 2007)

The enhanced conduction at low fields (<4 MV/cm) in metal-insulator semiconductor structures having nitrided oxides was recently explained using a generalized thermionic trap-assisted tunneling model. In the present work, we show that the same model can predict both high and low field leakage currents if we assume that a fraction (~35%) of the insulator thickness located next to the metal-insulator junction is devoid of traps. © *2007 American Institute of Physics*.
[DOI: 10.1063/1.2736650]

Trap-assisted tunneling is established as a dominant leakage current mechanism in the nitrided and tunnel oxides.[1–5] In our recent work,[5] we proposed a generalized thermionic trap-assisted tunneling (GTTT) model to explain the enhanced leakage current in nitrided oxides at low fields (<4 MV/cm). GTTT model considers tunneling through both triangular and trapezoidal barriers present in metal-insulator semiconductor (MIS) structures (see Fig. 1). In the present work, we show that the same model can predict both high and low field leakage currents if we assume that a thin region of width X_a located next to the metal-insulator junction is devoid of traps (see Fig. 2).

The GTTT model proposed earlier[5] assumed the traps to be present throughout the insulator thickness. The GTTT current calculated based on this assumption increases rapidly at high fields and thus deviates from the measured data. An analysis of this calculation (see Fig. 3) shows that the current flows through the trapezoidal barrier at low fields $E \leqslant (\phi_t/d)$ [see Fig. 1(a)], and mostly through triangular barrier at high fields $E \geqslant (\phi_t/d)$. This implies that the calculated triangular barrier component is much higher than the magnitude of this component in practice. As the electron tunneling switches from trapezoidal to triangular barrier at high fields, the traps located next to metal-insulator junction start participating in the tunneling process. Hence, reduction in the concentration of these traps can reduce the triangular barrier component appropriately to match modeled and measured data. For simplicity, we assume the traps to be totally absent over a thin region located next to the metal-insulator junction.

The mathematical representation of the GTTT model with the assumption that traps are absent over a width X_a next to the metal-insulator junction is obtained by modifying the basic equations (1) and (2) of Ref. 5 as follows, and can be understood with reference to Fig. 2.

$$J_{\rm GTTT} = \frac{qC_tN_t}{E}\left[\int_{\phi_t+E^*X_a}^{\phi_t+E^*d}\left(\frac{1}{f_{\rm FD}P_1}+\frac{1}{P_{2\_\rm trapezoid}}\right)^{-1}d\phi\right]$$
$$\text{for } E \leqslant \frac{\phi_t}{d-X_a}, \quad (1)$$

$$J_{\rm GTTT} = \frac{qC_tN_t}{E}\left[\int_{\phi_t+E^*X_a}^{E^*d}\left(\frac{1}{f_{\rm FD}P_1}+\frac{1}{P_{2\_\rm triangle}}\right)^{-1}d\phi + \int_{E^*d}^{\phi_t+E^*d}\left(\frac{1}{f_{\rm FD}P_1}+\frac{1}{P_{2\_\rm trapezoid}}\right)^{-1}d\phi\right]$$
$$\text{for } E > \frac{\phi_t}{d-X_a}, \quad (2)$$

Here, E is the electric field across the insulator of thickness d, C_t is the trap energy dependent rate constant, $f_{\rm FD}$ is the Fermi-Dirac function, and P_1, $P_{2\_\rm triangle}$, and $P_{2\_\rm trapezoid}$ are the tunneling probabilities based on the WKB approximation for two-step tunneling process (see Fig. 2). The terms $f_{\rm FD}$, P_1, P_2, and C_t are given by[5]

$$f_{\rm FD} = \frac{1}{1+\exp[q(\phi_B-\phi)/kT]}, \quad (3)$$

$$P_1 = \exp\left\{-\frac{\alpha}{E}[\phi^{3/2}-\phi_t^{3/2}]\right\}, \quad (4)$$

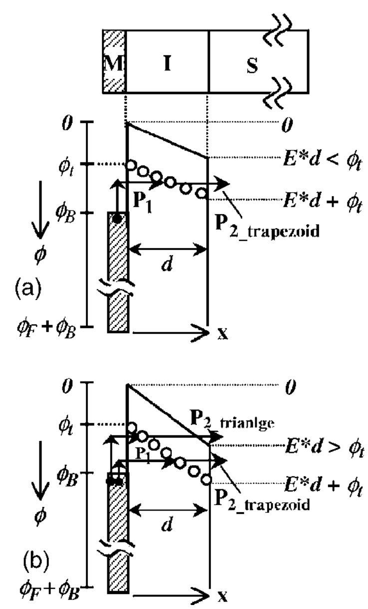

FIG. 1. Energy band diagram of a reverse biased MIS structure for low fields, $E^*d < \phi_t$ (a) and high fields $E^*d > \phi_t$ (b).

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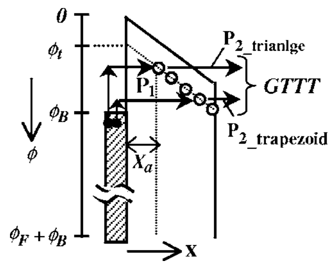

FIG. 2. Energy band diagram of a reverse biased MIS structure showing the insulator width X_a which is devoid of traps.

$$P_{2\_\mathrm{triangle}}=\exp\left\{-\frac{\alpha}{E}\phi_t^{3/2}\right\}, \tag{5}$$

$$P_{2\_\mathrm{trapezoid}}=\exp\left\{-\frac{\alpha}{E}(\phi_t^{3/2}-[\phi-E^{*}d]^{3/2})\right\},$$

$$\alpha=\frac{8\pi\sqrt{2m_I q}}{3h} \tag{6}$$

$$C_t=\left(\frac{m_M}{m_I}\right)^{5/2}\frac{16\pi q\phi_1^{3/2}}{3h\sqrt{\phi_t-0.2}}. \tag{7}$$

In (3), the barrier height ϕ_B is estimated including image force and quantum barrier lowering as per the relation[6]

$$\phi_B=\phi_{B0}-\alpha E^{1/2}-\beta E^{2/3}. \tag{8}$$

The other parameters ϕ_{B0}, N_t, ϕ_t, m_I, m_M, α, and β are explained in Table I. As shown in Fig. 3, the calculated triangular component is reduced as X_a is increased to 23 Å. Considering devices having nitrided oxide thicknesses of 74 Å (Ref. 2) and 60 Å (Ref. 4), we shall now establish that the measured leakage current through the insulator can only be predicted assuming $X_a\sim 35\%$ of the insulator thickness.

For device 1 with 74 Å insulator thickness,[2] the calculated GTTT current matches with the measured leakage current for X_a=26 Å (see Fig. 4). Table I gives the parameters

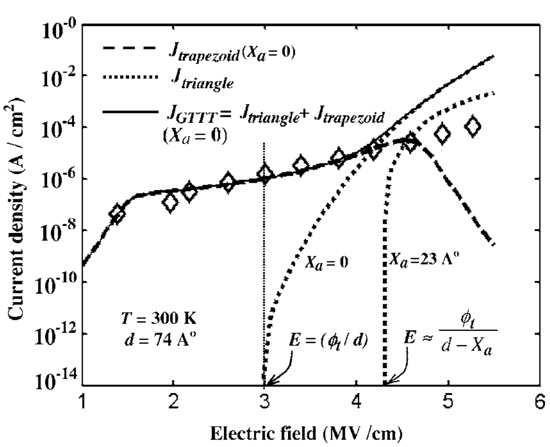

FIG. 3. Calculated total tunneling current (J_{GTTT}) together with its triangular (J_{triangle}) and trapezoidal ($J_{\mathrm{trapezoid}}$) components. Calculations use Eqs. (1)–(6) in Ref. 5 and parameter values from Ref. 5 which are reproduced here in Table I in the Device 1 column. Triangular component (J_{triangle}) is shown for X_a=0 and 23 Å. Points show the measured current through a 74 Å thick nitrided oxide (Ref. 2).

TABLE I. Parameters used in GTTT and DT current calculations.

S. No.	Model parameter	Description	Value: Device 1	Value: Device 2
1	ϕ_{B0}(V)	Schottky barrier height at 0 K excluding image force barrier lowering	3.2	3.2
2	ϕ_t(V)	Trap energy level	2.2	2.9
3	N_t(cm^{-3})	Trap concentration	6×10^{22}	1×10^{20}
4	X_a(A^0)	Insulator width devoid of traps	26	21
5	α[V(MV/cm)$^{-1/2}$]	Image force barrier lowering parameter	0.259[a]	0
6	β[V(MV/cm)$^{-2/3}$]	Quantum barrier lowering parameter	0.1[a]	0
7	m_I	Effective mass of electron in insulator	$0.42m_0$[b]	$0.42m_0$
8	m_M	Effective mass of electron in metal	$0.1m_0$[c]	$0.1m_0$

[a]Reference 6.
[b]Reference 2.
[c]Reference 3.

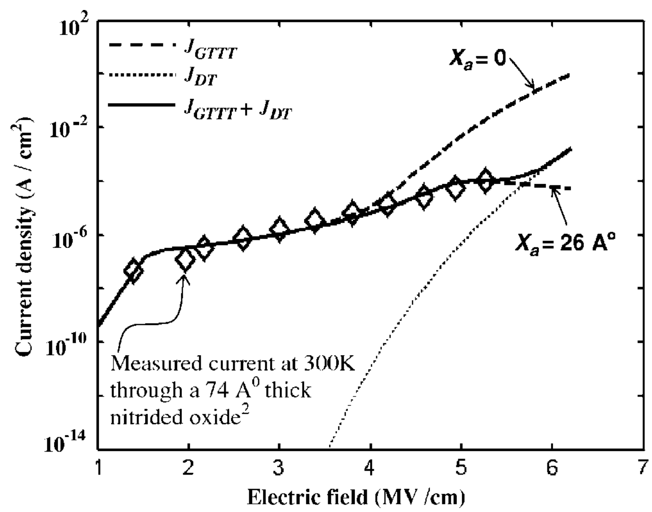

FIG. 4. Model fit (solid line) to experimental data (points) from Ref. 2 using the parameter values given in Table I for device 1. Also shown is the direct tunneling (DT) current which overtakes the GTTT current at ~5.5 MV/cm.

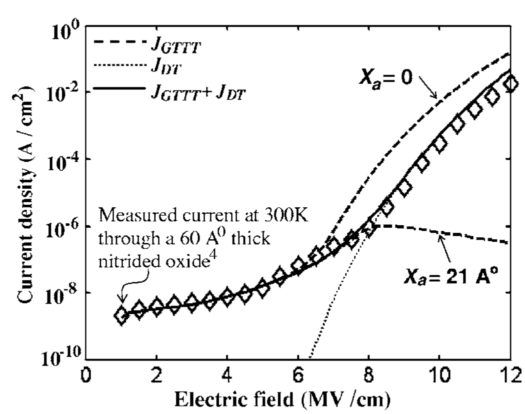

FIG. 5. Model fit (solid line) to experimental data (points) from Ref. 4 using the parameter values given in Table I for device 2. Also shown is the direct tunneling (DT) current which overtakes the GTTT current at ~8 MV/cm.

employed in the GTTT current calculations using Eqs. (1)–(8). Parameters 1–4 are primary parameters and the remaining parameters are secondary parameters. Primary parameters (1–4) are extracted from the best GTTT model fit to the measured data. Secondary parameters (5–8) are assumed based on the material properties. The parameter values except X_a given in Table I are the same as in our earlier work.[5] Note that the direct tunneling (DT) current exists in parallel with the GTTT current. The DT current includes the thermionic field emission (TFE) and field emission (FE) currents. We have calculated this current using the unified TFE-FE model reported in Ref. 7 and parameters 1 and 5–7 given in Table I. For device 2 with 60 Å insulator thickness,[4] the measured data can be predicted over a wide range of electric field (1–12 MV/cm) using X_a=21 Å and other parameters given in Table I (see Fig. 5). Note that DT current overtakes the GTTT current at high fields.

In summary, we have shown that the measured leakage current through thin nitrided oxides can be predicted over a wide range of fields from low to high using a GTTT model which assumes that a fraction (~35%) of the insulator thickness located next to the metal-insulator junction in MIS structures is devoid of traps.

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