# Briefs

## Thermionic Emission Probability for Semiconductor–Insulator Interfaces

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*Abstract*—**Simulation of hot-carrier gate-current effects in either MOSFET or MODFET devices requires knowledge of the carrier-emission probability over the semiconductor-insulator barrier. Several works in the recent past have relied on a limiting form for this probability that can lead to significant errors for large fields in the Si–$SiO_2$ system. This brief shows that the result for emission probability can be expressed as an error function, leading to simple implementation in the numerical 2-D simulators commonly used in device analysis. The result is compared to the commonly used limiting form for both large and small values of the normalized barrier height.**

### I. Introduction

Gate currents are important factors for both MOSFET's [1] and MODFET's [2]. In particular, simulation of the gate current in MOS structures is coming closer to reality. Empirical models [1] have led to 2-D simulators [3] that can explain, in part, the observed gate current. These models and simulators are typically based on the theory of charge emission from the semiconductor into the insulator [4]–[6]. The theories usually make an approximation and look at the analytical form for the emission when the carrier energy is only slightly larger than the band barrier. The approximate form, however, is integrated over the entire range of the carrier energy, leading to a contradiction between the approximation and the calculation. The contradiction can result in overestimation of the emission probability by a significant amount for small normalized barrier heights, analogous to small barrier heights, large electric fields, or long scattering mean free paths at the interface.

### II. Derivation

We begin by recalculating the emission probability given by [1, eq. (3)], without the limiting condition used in [1, eq. (1)]. Some of the relevant quantities of the calculation are shown in Fig. 1. The accelerating field for carrier transport to the insulator interface is the lateral field $E_x$. $\lambda$ is the scattering mean free path in the semiconductor; for hot carriers in Si, this is principally the optical phonon-scattering mean free path. $\phi_B$ is the explicit barrier height, and $\Delta\phi$ the carrier potential in excess of this height. The probability of having both the proper momentum and energy for surmounting the insulator barrier is then [1]

$$P_{\phi_B} = \int_{\Delta\phi=0}^{\Delta\phi=\infty} d(\Delta\phi)\,\frac{1}{2E_x\lambda}\left[1-\left(\frac{\phi_B}{\phi_B+\Delta\phi}\right)^{1/2}\right] \cdot \exp\left\{-\left[\frac{\phi_B+\Delta\phi}{E_x\lambda}\right]\right\}. \quad (1)$$

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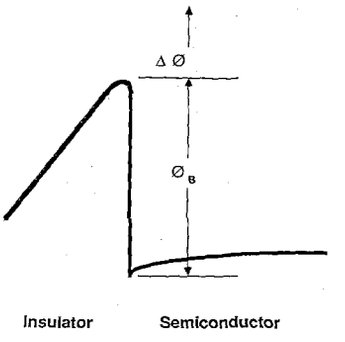


Fig. 1. Band diagram for thermionic emission. Parameters used in the derivation are as shown.

The previous models [1], [4] and simulator [3] make the approximation that $\Delta\phi \ll \phi_B$—but then integrate over the full range of $\Delta\phi$. Resisting this, let

$$k = \frac{1}{2E_x\lambda}\exp\left(-\frac{\phi_B}{E_x\lambda}\right). \quad (2)$$

Change the variable $\Delta\phi$ to $x$. Then

$$P_{\phi_B} = k\int_{x=0}^{x=\infty} dx\left[1-\left(\frac{\phi_B}{\phi_B+x}\right)^{1/2}\right]\exp\left\{-\left[\frac{x}{E_x\lambda}\right]\right\} \quad (3)$$

which gives

$$= k\left\{E_x\lambda - \int_{x=0}^{x=\infty} dx\left(\frac{\phi_B}{\phi_B+x}\right)^{1/2}\exp\left(-\frac{x}{E_x\lambda}\right)\right\}. \quad (4)$$

The integral is evaluated easily using [7]

$$P_{\phi_B} = \frac{1}{2}\left\{\exp\left(-\frac{\phi_B}{E_x\lambda}\right) - \left(\frac{\pi\phi_B}{E_x\lambda}\right)^{1/2}\operatorname{erfc}\left[\left(\frac{\phi_B}{E_x\lambda}\right)^{1/2}\right]\right\} \quad (5)$$

where erfc is the complementary error function commonly found in analytical treatments of dopant diffusion in semiconductors.

This form includes no approximations, and is simple enough to be included in 2-D simulators. Since, as the next section shows, this form and the approximate result can differ significantly, it is important to include the correct result in calculations of emission probability.

### III. Discussion

In Fig. 2, we plot [1, eq. (3)], where $\Delta\phi$ is presumed to be small, versus the result from the previous section. The complementary error function is calculated in standard fashion, according to

$$\operatorname{erfc}(x) = 1 - \operatorname{erf}(x) = 1 - \frac{2}{(\pi)^{1/2}}\int_0^x dt\, e^{-t^2}. \quad (6)$$

The probability is plotted versus the normalized variable $\phi_B/E_x\lambda$. Both numerical integration of erfc $(x)$ and the polynomial form in [8] were examined; they were identical within tenths of a percent over the range of the normalized parameter shown. For small values of the parameter, significant overprediction of the thermionic emission probability can result from the use of the ap-

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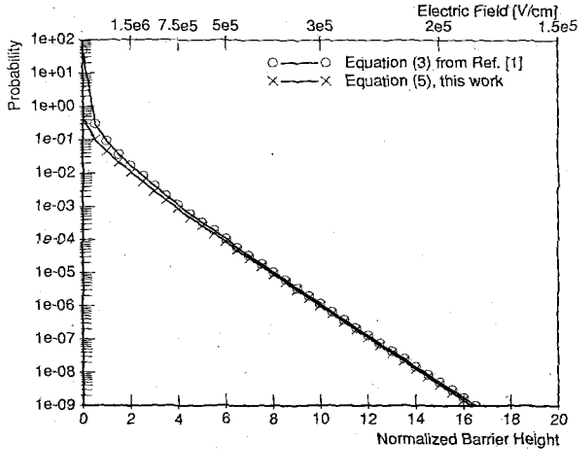


Fig. 2. Emission probability versus large normalized barrier height $\phi_B/E_x\lambda$. $\lambda = 100$ Å and $\phi_B = 3.0$ V.

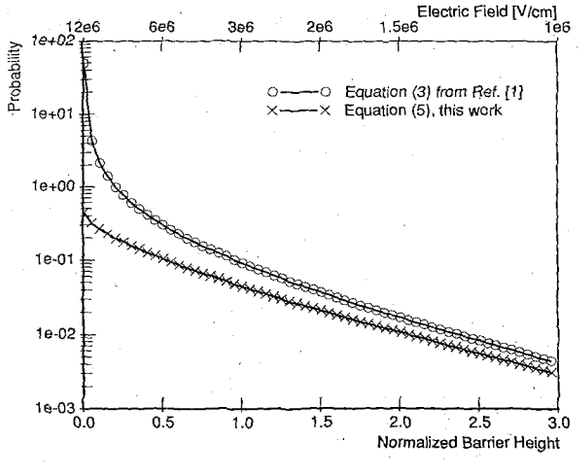


Fig. 3. Emission probability versus small normalized barrier height $\phi_B/E_x\lambda$. $\lambda = 100$ Å and $\phi_B = 3.0$ V.

proximate form, as shown in Fig. 3. This range corresponds to fields of roughly 1.0 MV/cm in the Si–$SiO_2$ system, using a mean free path for electron optical phonon scattering of 100 Å. Such fields may be found in modern scaled MOS devices—particularly EPROM's and EEPROM's, where use of an accurate expression for the thermionic probability will be even more important. In MODFET's, with smaller barrier heights and longer mean free paths, the fields requiring the accurate expression are much smaller.

While $E_x$, the lateral field in a MOSFET, is the proper field to use in calculating channel hot-carrier (CHC) contributions to the MOS gate current, the total field at the generation point for the impact-ionized substrate current [1], [9] will be important in the drain-avalanche hot-carrier (DAHC) regime. This occurs since the DAHC gate current often is composed principally of holes, transported to the interface by the vertical field $E_y$ between the gate and drain. The vertical fields near the device drain can exceed 1.0 MV/cm, requiring proper use of the full thermionic-emission probability to model the gate current in this regime.

## IV. Conclusion

We have shown that the emission probability used by existing models and simulators for the calculation of the gate current in MIS devices is an approximate one, which can result in overestimation of the emission probability by a large factor for a large electric field, a large mean free path, or a small barrier height. The full emission probability is derived, and is shown to be a relatively simple function that lends itself to 2-D numerical simulation. The new expression has particular application to simulation of the gate current in MOSFET and MODFET devices.

## Acknowledgment

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## References

[1] S. Tam *et al.*, "Lucky-electron model of channel hot-electron injection in MOSFET's," *IEEE Trans. Electron Devices*, vol. ED-31, p. 1116, 1984.
[2] J. H. Baek *et al.*, "New mechanism of gate current in heterostructure insulated gate field-effect transistors," *IEEE Electron Device Lett.*, vol. EDL-7, p. 519, 1986.
[3] S. Baba *et al.*, "Mechanism of hot carrier induced degradation in MOSFET's," in *IEDM Tech. Dig. Papers*, p. 734, 1986.
[4] A. Phillips, Jr. *et al.*, "IGFET hot electron emission model," in *IEDM Tech. Dig.*, p. 39, 1975.
[5] C. N. Berglund and R. J. Powell, "Photoinjection into $SiO_2$: Electron scattering in the image force potential well," *J. Appl. Phys.*, vol. 42, p. 573, 1971.
[6] T. Ning *et al.*, "Emission probability of hot electrons from silicon into silicon dioxide," *J. Appl. Phys.*, vol. 48, p. 286, 1977.
[7] I. S. Gradshteyn and I. M. Ryzhik, *Tables of Internals, Series, and Products*. New York: Academic, 1980, p. 315.
[8] M. Abramowitz and I. Stegun, *Handbook of Mathematical Functions*. New York: Dover, 1970, eq. 7.1.26.
[9] A. K. Henning *et al.*, "Substrate current at cryogenic temperatures: measurements, and a two-dimensional model for CMOS technology," *IEEE Trans. Electron Devices*, vol. ED-34, p. 64, 1987.

# Pseudocollector Effect in a CMOS Inverter

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***Abstract*—The pseudocollector effect in a CMOS inverter is demonstrated by analyzing the current distribution in the latchup state. The decoupling of the current flow from the latchup feedback loop is controlled by the input voltage applied to the gates of n- and p-channel MOSFET's, which results in a reduction of latchup susceptibility. Latchup in a CMOS inverter is influenced by the input voltage through pseudocollector and potential modulation effects. A simple SCR structure cannot reflect adequately these phenomena.**

## I. Introduction

Latchup in CMOS integrated circuits has been studied extensively over the past decade. The structure frequently used in latchup studies is a p-n-p-n semiconductor-controlled rectifier (SCR) formed by nonfloating diffusions, a well, and a substrate because of its simplicity and ease of modeling [1]–[5]. For latchup to occur, currents in the substrate or well must forward bias a diffusion-background junction that forms the emitter and base of a parasitic bipolar transistor. However, little study has been done to

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