LOW TEMPERATURE GATE CURRENT AND "CHANNEL" HOT CARRIERS IN MOS TRANSISTORS

Albert K. Henning
Thayer School of Engineering
Dartmouth College
Hanover, NH 03755

Emission of electrons and holes from MOSFET channels across the insulator barrier is of fundmental interest, due to the material damage caused by this transport and subsequent effects on device speed and reliability. The gate current vs. gate voltage characteristic has been most widely used in measuring gate currents. Traditionally, it is divided into two regimes, each related to the charges held to be responsible: channel hot carriers (CHC); and drain-avalanche hot carriers (DAHC). The CHC regime is believed to be caused by MOSFET inversion channel carriers which go through a several-step process of: heating and occupation of high-energy states; scattering toward the interface; transport to the interface; and emission into the insulator. This work re-examines the "channel" hot-carrier regime. It is concluded that experimental observations previously attributed to CHC can be explained by DAHC processes alone. Furthermore, it is shown that the temperature behavior of these gate currents cannot be explained by the traditional CHC process.

Phillips, *et al.* [1], gave the first simulation results of hot-carrier gate currents in MOSFETs. Their model relied on a charge generation term at each location in the device channel, and explored the probability the generated charge was scattered toward the MOSFET interface. They did not give a physical basis for the charge generation. Transport to the interface was determined in part by Shockley's lucky-electron process. Hu [2] and Tam, *et al.* [3] stated the generated charge term for the CHC regime of the I_G vs. V_G characteristic was due to channel hot carriers which were scattered toward the interface (see Figure 1). They continued the lucky-electron model for emission into the insulator. A variety of other authors have modeled both hole and electron components of gate current in, particularly, NMOSFETs. Most recently, Chen and Tang [4] have added more extensive treatments of scattering probabilties, but the basic model of Phillips, *et al.*, and assumption of channel hot carriers as dominant have remained intact.

All analyses to date, however, which assume channel hot carriers dominate have neglected the relationship between scattering rate and the number of optical phonons, which are assumed to be responsible for the momentum changes in channel hot carriers which propel them toward the gate interface. In particular, the number of optical phonons decreases exponentially as temperature decreases, in marked contrast to the increases observed in electron gate current noted in NMOSFETs for such temperature decreases (see Figure 2 [5]).

Consider the following probabilities contributing to possible channel hot carrier injection: a) scattering of a hot channel carrier by an optical phonon, with scattering time τ_{op}; b) transport of these scattered carriers ballistically to the interface (lucky-electron process, mean free path l); c) emission of those carriers with enough energy to surmount the Si-SiO$_2$ interfacial barrier. If the hot carriers, prior to scattering, are described by a Maxwell-Boltzmann distribution, then the gate current can be written as:

$$I_{g,che} = \int_{\Delta E_c - \Delta V}^{\infty} \frac{dE}{(kT_e)^2} \frac{q}{\tau_{op}} E \exp\left(-\frac{E}{kT_e}\right) \exp\left(-\frac{d}{\lambda}\right)$$

T_e is the electron temperature characteristic of the distribution, d is the distance from the generation point to the injection point, ΔV is the ballistic energy gained in going the distance d, and ΔE_c is the Si-SiO$_2$ barrier height at the injection point. The τ_{op} term has not been considered before, and includes several important effects, principally the density of optical phonons as a function of temperature [6]:

$$\frac{1}{\tau_{op}} \approx \exp\left(-\frac{E_{op}}{kT_{lattice}}\right) \sqrt{E}$$

The scattering rate increases with increasing electron energy due to the density of states, but decreases with lattice temperature due to the decrease in the number of optical phonons present to do the scattering. This additional factor overrides increases in $I_{g,\ che}$ due to increased mean free path at low temperature, and decreased transport distance (due to average channel charge lying closer to the interface at LT).

To demonstrate this, consider the following. Assume T_e, d, and ΔV are roughly constant as the temperature decreases from room temperature to 77K. Then the temperature dependence of I_G is contained in the exp $(-d/\lambda)$ and τ_{op} terms. It has been established [3] that the temperature dependence of λ is given by:

$$\lambda = \lambda_0 \tan h\,(x)$$

where $x = E_{op}/kT$, $\lambda_0 = 100$ Å, and $E_{op} = 0.063$ eV. To simplify the comparison of I_G with and without consideration of optical phonons, let d = 1000 Å (carriers start 0.1 µm beneath the Si-SiO$_2$ interface). Then:

$$I_G^{with}\,(x) \propto \exp\left[-x - \frac{10}{\tan h\,(x)}\right]$$

$$I_G^{without}\,(x) \propto \exp\left[-\frac{10}{\tan h\,(x)}\right]$$

Table 1 shows the comparison, also evident from dividing these two expressions.

Table 1

x	T(K)	I_G^{with} (x)	$I_G^{without}$ (x)
1	731	7.3×10^{-7}	1.98×10^{-6}
2	657.9	4.23×10^{-6}	3.13×10^{-5}
3	584.8	2.15×10^{-6}	4.32×10^{-5}
4	511.7	8.26×10^{-7}	4.51×10^{-5}
5	438.6	3.06×10^{-7}	4.54×10^{-5}
6	365.5	1.13×10^{-7}	4.54×10^{-5}
7	292.4	4.14×10^{-8}	4.54×10^{-5}
8	219.3	1.52×10^{-8}	4.54×10^{-5}
9	146.2	5.60×10^{-9}	4.54×10^{-5}
10	73.1	2.06×10^{-9}	4.54×10^{-5}

This analysis, then, demonstrates that scattering of channel hot carriers cannot explain the temperature dependence of the observed I_G vs. V_G characteristic. As a result, drain avalanche hot carriers (DAHC) are left to explain the experimental observations. Since they include both electrons and holes, because of their origin in impact ionization, the whole spectrum of I_G, I_B, and I_D observations can be explained, by following impact ionized charges from their generation point to collection at either gate, source, or drain [7]. Finally, though the microscopic, physical basis for gate current is altered by this analysis, the empirical relationships developed in [2, 3] remain valid, since impact ionization (leading now to both substrate and all gate currents) is still explained by lucky-electron concepts.

References

[1] A. Phillips, Jr. *et al.*, *IEDM* 1975, p. 39.
[2] C. Hu, *IEDM* 1979, p. 22.
[3] S. Tam, *et al.*, *IEEE Trans. Elec. Dev.*, **ED-31**, p. 1116, 1984.
[4] Y.-Z. Chen and T.-W. Tang, *IEEE Trans. Elec. Dev.*, **ED-35**, p. 2180, 1988.
[5] A. K. Henning, Stanford (U.) Elec. Lab. Tech. Rep. G725-1, p. 134, 1987.
[6] K. Hess, Advanced Theory of Semiconductor Devices, p. 93 (Prentice-Hall, 1988).
[7] A. K. Henning, in Proc. October 1988 Electrochemical Soc. Mtg.

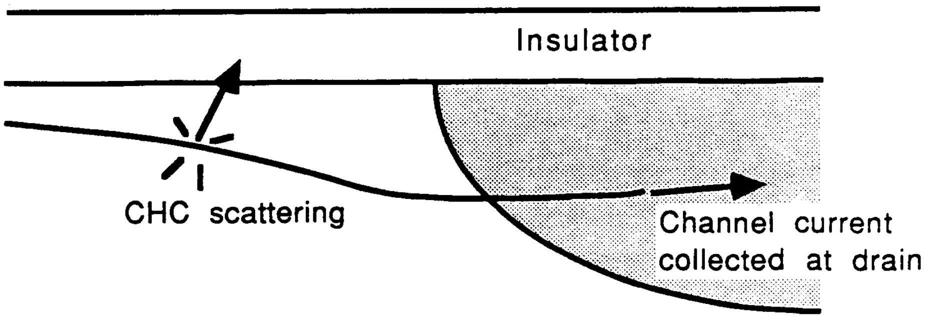

Figure One: CHC gate emission process, after [2, 3]

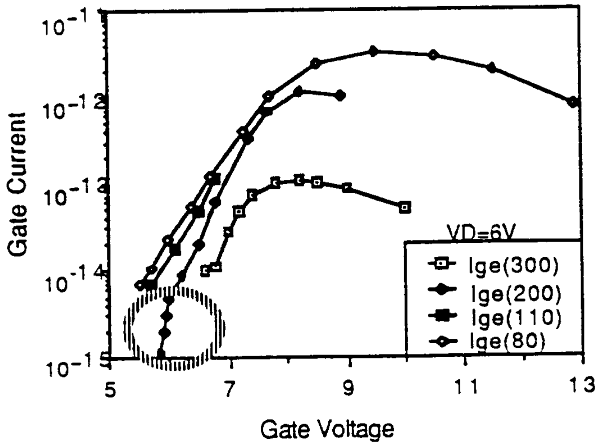

Figure Two: Temperature characteristics of gate current measured with the floating gate technique.

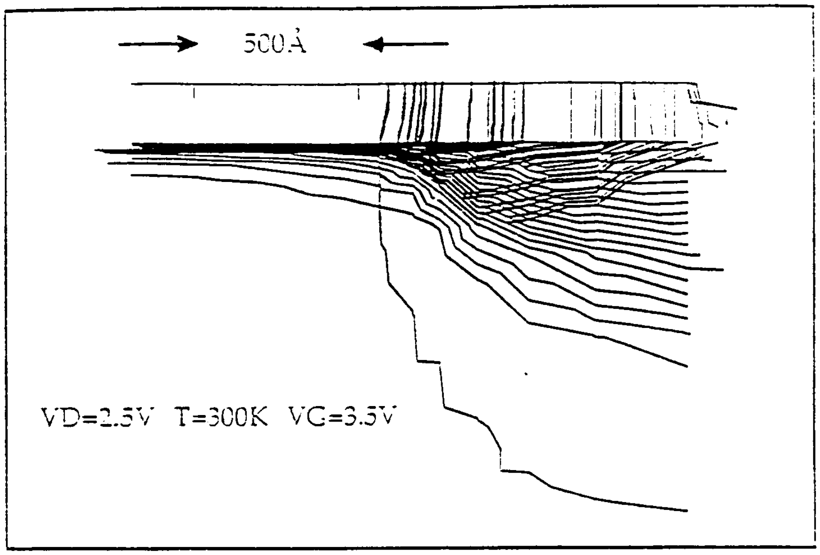

Figure Three: (Top) DAHC process showing channel current contours, and electron gate current contours plotted by following the drift of impact ionized carriers from generation point to the interface. (Bottom) A similar plot, this time following impact ionized holes. Both plots were generated using PISCES, simulating a 0.8μm Le NMOS device.