Electron Dynamics in Short Channel Field-Effect Transistors

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Abstract—The dynamics of electrons between the source and drain of a microwave field-effect transistor (FET) have been studied using a Monte Carlo method. The spatial dependence as well as the time dependence of the average electron velocity is presented. It is shown that in silicon the relaxation time is short enough not to influence the figure of merit of the transistor. However, in direct gap polar semiconductors (e.g., GaAs), the electrons can have a velocity well above their saturation value for an appreciable length of time and, consequently, over a distance nonnegligible compared to the length of the active region of a high frequency FET. This could improve the figure of merit of the FET.

I. INTRODUCTION

In a recent analysis [1] of the microwave field-effect transistor (FET) it has been shown that when the electric field in the conducting channel is larger than the critical field \( E_c \) (see Fig. 1) the transconductance \( g_m \) is proportional to the saturation velocity of the carriers in the semiconductor considered. Also, Drangeid and Sommerhalder [1] have advocated the use of GaAs for such application, instead of Si, because of its higher saturation velocity \( v_s \) which in fact differs, if higher, by no more than 10 percent from the value obtained in silicon. However, as seen in Fig. 1(a), GaAs exhibits a peak velocity prior to saturation. By a judicious choice of the bias field \( E \) (2 kV/cm < \( E < 5 \) kV/cm) the figure of merit \( f_{\text{max}} \) could be improved but not as drastically as experimental data [2] taken at an average field over 8 kV/cm seem to indicate.

To resolve this discrepancy, we used a Monte Carlo method to study the dynamics of cold electrons injected at the source. The time and spatial dependence of the drift velocity were derived. Because, in the high-frequency FET, the separation between source and drain is in the micron range, the transit time of the carriers between those two electrodes becomes comparable to the relaxation time of electrons in the semiconductor. Therefore, cold electrons injected at the source may never reach their steady-state velocity before being collected at the drain but travel at a higher velocity \( v \) before relaxation effects take place given by

\[
v \approx \mu_0 E
\]

where \( \mu_0 \) is the initial mobility. The relaxation effect will modify the shape of the distribution function corresponding to an increase in the temperature of the electron system, and the average velocity \( v \) will depart from Ohm's law. The transient nature of injection and transit processes allows the average velocity to overshoot the usual saturation value. This phenomenon is due to the nonequivalence of energy relaxation times and momentum relaxation times.

II. THE MODEL

The model of the band structure and scattering mechanisms and the materials parameters used in the present work are the same as described previously [3] and will only be briefly discussed here. The materials parameters are listed for convenience in Table I.

The nonparabolicity of the (000) minimum in the conduction band is included, while the (100) minima are assumed to lie at the zone edges with spherical constant energy surfaces. In GaAs, polar and acoustic scattering are considered in the (000) valley. The admixture of p-type valence band wave function into the (000) conduction band states is included in the calculation of the scattering rates in this valley and also in calculating the intervalley scattering rate between the (000) and (100) minima. In silicon, acoustic and equivalent intervalley scattering between the (100) minima are considered.

The Monte Carlo procedure used to generate random numbers to represent the time that the electron drifts freely in the electric field, the process responsible for scattering the electron, and the final state after the scattering, is identical with that used previously [3].

In practical FET devices, the electric field is a function of time and space. The present calculation assumes, however, a spatially uniform electric field between source

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and drain. The response of the average electron is obtained by following a large number of electrons in momentum space and recording their trajectories. The initial momentum of the electrons is distributed according to the equilibrium momentum distribution function corresponding to the lattice temperature.

In order to determine the high-field distribution function, histograms are set up that record the trajectory of the electrons in a three-dimensional space $(k_x, k_y, t)$ where $k_x$ and $k_y$ are, respectively, the component of the momentum parallel and perpendicular to the electric field and $t$ is the time. The time that the electron spends in a particular cell is proportional to the distribution function at this point in $(k_x, k_y, t)$ space. Consequently, by recording the time component of the electron trajectory in $(k_x, k_y, t)$ space, the time evolution of the distribution function can be easily obtained. The transitions between states due to the various scattering processes are taken to be instantaneous.

III. RESULTS AND DISCUSSION

We show in Fig. 2 the time dependence of the average velocity of the electrons injected cold at the cathode and drifting in a region of uniform electric field for both silicon and gallium-arsenide. We first note that for both silicon and gallium-arsenide, the velocity overshoots the saturation value for high fields. This can be understood in view of the disparity of the momentum and energy relaxation times in both of those materials. As the momentum relaxation time is smaller, the electron distribution is first shifted in momentum space. Somewhat later, energy relaxation becomes effective so that the distribution function spreads, and the drift velocity decreases. Because of strong intervalley and acoustic scattering in silicon, the drift velocity reaches its saturation value in less than 0.1 ps. In GaAs, the relatively weak polar optical scattering is dominant so that transient effects last an order of magnitude longer than in silicon.

One should also notice that in silicon the transient times increase slightly with electric field. The same behavior is observed in GaAs for relatively low electric field (<5 kV/cm). However, for higher electric field the transient time starts to decrease again for GaAs. This effect is due to strong nonequivalent intervalley scattering processes that occur when the energy of the electron exceeds the energy separation $\Delta = 0.36$ eV between the central and satellite valleys.

Fig. 3 is more relevant to high-frequency transistors and shows the drift velocity as a function of distance from the source. In silicon, the distance over which the drift velocity overshoots the saturation value is negli-

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TABLE I
PARAMETERS USED IN CALCULATIONS

<table>
<thead>
<tr>
<th>Scattering Process</th>
<th>Parameters</th>
<th>GaAs (000) Valley</th>
<th>GaAs (100) Valley</th>
<th>Si (100) Valley</th>
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<tr>
<td>polar optic</td>
<td>effective mass</td>
<td>0.067</td>
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<td>0.39</td>
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<td></td>
<td>static dielectric constant</td>
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<td>optical dielectric constant</td>
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<td></td>
<td>longitudinal optic phonon energy (eV)</td>
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<td>acoustic</td>
<td>deformation potential (eV)</td>
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<td>6.55</td>
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<td></td>
<td>velocity of sound (cm s⁻¹)</td>
<td>5.22X10⁶</td>
<td>9.05X10⁶</td>
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<td>(100)-(100) intervalley</td>
<td>coupling constant (eV cm⁻¹)</td>
<td>1X10⁹</td>
<td>3.5X10⁷</td>
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<tr>
<td>(000)-(100) intervalley</td>
<td>phonon energy (eV)</td>
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</table>
Fig. 3. Electron drift velocity as a function of distance. Top graph corresponds to Si and bottom graph to GaAs.

gible compared to the usual dimensions of transistors and consequently is of no effect. This situation is drastically changed for GaAs where the electrons travel at a velocity above their steady-state value for more than 1 \( \mu \text{m} \) at a field of 5 kV/cm. This value of the field was not optimized for obtaining the maximum distance of high-velocity propagation.

From these results, we can speculate that the use of direct-gap polar semiconductors with weak polar optical scattering and large central-to-satellite valley energy separations would assure a large energy relaxation time and could improve the figure of merit of FET’s. Promising candidates could be InAs and InAs\(_{x-1}\)P\(_x\).

Comparison with experiment is complicated by a lack of experimental data. However, it seems unlikely that the overshoot of the drift velocity alone can explain the high figure of merit [2] of GaAs FET’s. The lower resistive parasitics could be substantial in increasing the figure of merit.

Finally, in Fig. 4, we show for GaAs the distance of travel of the electrons as a function of time. A complete family of such curves, not presented here for economical reasons, can be used to make a choice of optimum electric fields to minimize the transit time of the electrons over a known distance between source and drain.

In conclusion, transient effects on the drift velocity of GaAs are important but probably not large enough to explain the remarkable performance of GaAs FET’s [2]. However, using polar material with weak polar optical scattering (InAs), it should be possible to improve this figure of merit even further.

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References