Substrate Current Fluctuation under Low Drain Voltages in Si-MOSFET's

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Abstract—**It is shown that anisotropy manifested by the wave-vector dependent impact ionization rates in Si leads to large fluctuation of the substrate current in Si-MOSFET's. This is especially true at low drain voltages under which the ionization events take place near ionization threshold, where anisotropy is greatest.**

I. INTRODUCTION

Long-term reliability of semiconductor devices is of great importance for a reliable operation of every semiconductor-based technology. Many device reliability issues are deeply related to impact ionization. Therefore, correct understanding of the impact ionization phenomena is one of the key elements to achieve the long-term stable operation of semiconductor devices [1]. Fortunately, we have recently reached, thanks to a series of theoretical and experimental investigations at various research institutes, a satisfactory agreement on the strength of the electron-initiated ionization rate in bulk Si; the energy dependence of the ionization rate per unit time is now well understood [2].

However, it has also been recognized that the impact ionization events in Si are strongly dependent of wave-vector of the primary electron and, thus, shows large anisotropy in low energy regions [3]. In spite of its large anisotropy (the ionization rate per unit time ranges over several orders of magnitudes near ionization threshold energy), it is still not clear what exactly this anisotropy affects on carrier transport characteristics and on device performance. In fact, the recent theoretical analyses show that the transport properties in *bulk-Si* are hardly affected by such anisotropy [4]. We shall demonstrate that this somewhat fortunate situation breaks down in short-channel Si-MOSFET's, *i.e.*, the intrinsic anisotropy of impact ionization could lead to fluctuation of the substrate current under low drain voltages.

It is important to notice that the substrate current generated through impact ionization inside the substrate is a direct measure of device lifetime [5], [6]. Since the fraction of high energy carriers which quasi-ballistically travel through the channel becomes greater as the channel-length is reduced [7], the phenomena related to impact ionization are expected to be still significant in very short-channel Si-MOSFET's. Furthermore, the applied drain voltage in such short devices is forced to be reduced and, thus, the substrate current fluctuation predicted in the present study could be also important from the device reliability view-point.

The present paper is organized as follows: In section II, we briefly describe a physical picture inherent in the substrate current fluctuation. In section III, the simulation results from the full-band Monte Carlo for short-channel Si-MOSFET's are presented. Summary is given in section IV.

II. PHYSICAL PICTURE

The substrate current in Si-MOSFET's is directly related to the hole generation rate associated with impact ionization taken place in Si substrate. If the transit time effect over which the generated holes travel through the substrate is ignored, the hole generation event could be regarded as a Dirac-pulse like event. Hence, the shot noise would appear on the substrate current. The shot noise on the substrate current is then related to how often the holes could be generated due to impact ionization, which is, of course, the ionization rate per unit time.

On the other hand, because of the recent miniaturization of devices, the reduction of the applied voltage is inevitable from the device reliability view-point. As a result, the high-energy tail above the applied drain voltage in the electron energy dis-

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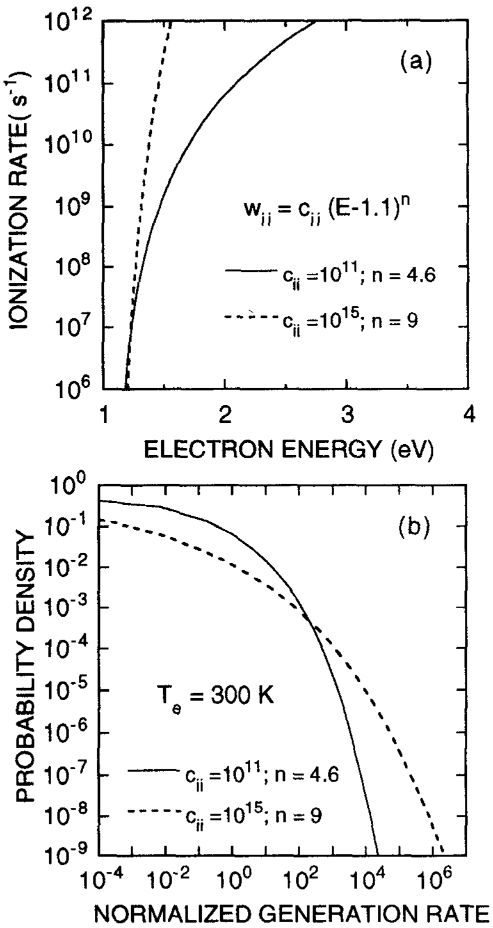

Fig. 1. **(a) Impact ionization rates evaluated from the Keldysh formula with two different parameters: soft ionization threshold (solid curve) and hard ionization threshold (dashed curve). (b) Probability density of hole generation rate. The hole generation rate is normalized by the averaged generation rate corresponding to the two different ionization rates given in (a).**

tributions is greatly narrowed [7]. This is equivalent to saying that the extent of the energy range, within which the electrons could possibly induce impact ionization, becomes narrower and closer to the ionization threshold energy. It should be noted that the ionization rate, in general, rises steeply near the ionization threshold energy. Therefore, the ionization rate changes its magnitudes greatly within that energy range and leads to fluctuation in the number of ionization events per unit time, *i.e.*, the hole generation rate.

The above scenario is roughly demonstrated in Fig. 1. Simple isotropic (energy-dependent) ionization rates are assumed and evaluated from the Keldysh formula with two different sets of parameters, as given in Fig. 1(a); the *soft* ionization rate fitted to the *ab-initio* rate in Si (solid curve) and the *hard* ionization rate having much steeper rise above ionization threshold (dashed curve). Assuming that the high-energy tail above the threshold energy in the electron energy distribution has a slope with the electron temperature $T_e = 300$ K, the hole generation probability could be evaluated. The results are shown in Fig. 1(b). It is clear that the hole could be generated over a wide range of time-scale for the case of *hard* ionization threshold. Indeed, the normalized standard deviation of the hole generation rate is, when the *hard* ionization threshold (solid curve) is used, over ten times larger than that of *soft* ionization threshold. This observation substantiates the scenario described above.

We would like to stress that the above argument is entirely based on the steep rise of the energy-dependent ionization rate. In addition, the ionization rate shows intrinsic anisotropy near the ionization threshold energy, *i.e.*, the ionization rate is dependent of wave-vector of the primary electrons. Hence, the fluctuation of the hole generation rate is expected to be more enhanced when intrinsic anisotropy is taken into account.

III. FLUCTUATION IN MOSFET's

Keeping the story discussed in section II in mind, the substrate current fluctuation has been investigated for short-channel Si-MOSFET's.

The full-band Monte Carlo method employed in the present study has already been described in [7]. The anisotropic ionization rates per unit time are evaluated from the constant-matrix-element (CME) approximation, that is a good approximation of the wave-vector dependent *ab-initio* ionization rates [8], [9]. For comparison, we have also employed the isotropic ionization rate obtained by averaging the wave-vector dependent ionization rates over equi-energy surfaces in the first Brillouin zone. The device structure we have employed is a typical MOSFET structure with two different gate lengths $L_g = 250$ and 40 nm, which, respectively, represent deep submicron and sub-0.1 micron devices.

From the discussion in section II, it is clear that the substrate current fluctuation is directly related to the width of the energy range in the electron energy distributions in which electrons possibly induce impact-ionization. Fig. 2 shows the effective ionization rates, defined as

$$w_{\text{eff}}(E) = \frac{\int d^3k \, w_{ii}(\mathbf{k}) \, f(\mathbf{k}) \, \delta(E - E(\mathbf{k}))}{\int d^3k \, f(\mathbf{k}) \delta(E - E(\mathbf{k}))}, \quad (1)$$

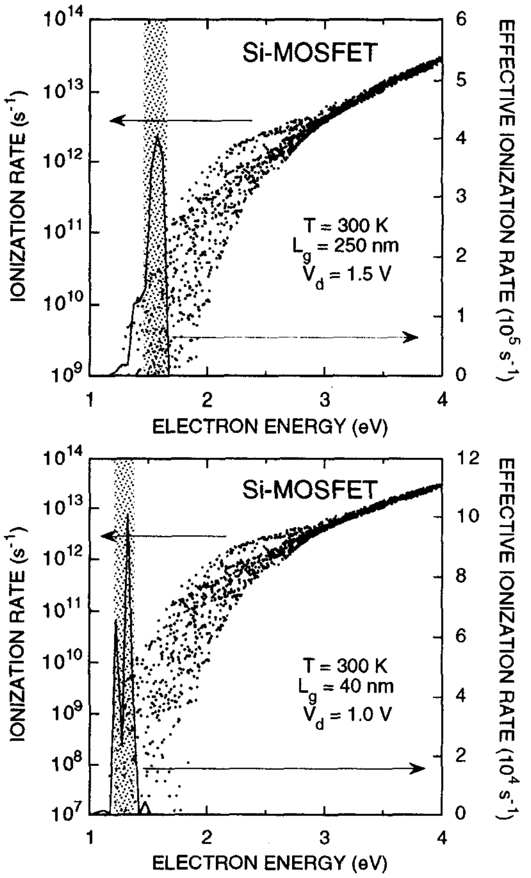

Fig. 2. Effective ionization rates in Si-MOSFET's with L_g = 250 and 40 nm (solid curves). The shaded regions schematically represent the width of the effective ionization rates. The wave-vector-dependent ionization rates are also plotted with dots as a function electron wave-vector.

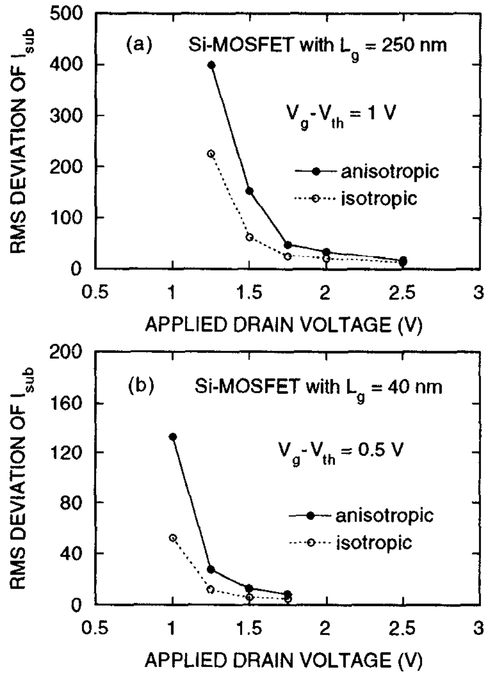

Fig. 3. Normalized standard deviation (root-mean-square deviation) of the substrate currents in Si-MOSFET's as a function of the applied drain voltage. The solid and dotted lines represent the results when the anisotropic and isotropic ionization rates, respectively, are used in the simulations.

as a function of electron energy. The effective ionization rate represents the effective width of that energy range in the electron energy distributions for each device. The energy range is dependent of the applied drain voltage and becomes very narrow under low drain voltages. Notice that the anisotropic ionization rates, also plotted with dots in the same figures, spread over many orders of magnitude in such energy regions. Therefore, the ionization events would take place with different time-scales and the substrate current is expected to fluctuate.

This is indeed the case; Fig. 3 shows the normalized standard deviation of the substrate current under various applied drain voltages in MOSFET's with L_g = 250 and 40 nm. The standard deviation obtained from the isotropic ionization rate is also plotted with dotted curves. It is interesting to note that the standard deviation increases as the applied drain voltage is reduced in both anisotropic and isotropic ionization rates used. This is somewhat consistent with characteristics in shot noise. The rare events such as carrier emission over the potential barrier or hole generation in the present study, both of which lead to shot noise, is approximated with the Poisson distribution [10]. Recall that the variance of the current under the Poisson distribution is proportional to the averaged current. Thus, the normalized standard deviation of the substrate current would be inversely proportional to the square-root of the substrate current,

$$\frac{\sqrt{(\Delta I_{sub})^2}}{I_{sub}} \propto \frac{1}{\sqrt{I_{sub}}}. \qquad (2)$$

Therefore, the standard deviation increases as the magnitude of the substrate current decreases. Furthermore, the fluctuation is more enhanced when anisotropy of the ionization rates is taken into account. Consequently, we may conclude that the intrinsic anisotropy of impact ionization in Si would lead to greater fluctuation of the substrate current.

We would like to stress that the time scale of the ionization processes is extremely short. The substrate current fluctuation is expected to take place on nano-seconds, or, equivalently, on GHz frequency ranges. In addition, the magnitude of the substrate current is very weak under low drain voltages and, thus, it might be difficult to directly confirm the present predictions from experiments. Possibilities to verify the substrate current (or hole generation) fluctuation via alternate approaches are now under investigation.

IV. SUMMARY

We have investigated the effects of anisotropy inherent in the impact ionization rates on the substrate current in short-channel Si-MOSFET's and shown that the intrinsic anisotropy leads to large fluctuation of the substrate current under low drain voltages. This fluctuation is expected to become greater as the device size shrinks because of the reduction of applied drain voltages.

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REFERENCES

[1] For example, C. T. Wang, *Hot Carrier Design Considerations for MOS Devices and Circuits*, Van Nostrand Reinhold, New York, 1992.

[2] The present status is summarized by M. V. Fischetti and S. E. Laux, "Monte Carlo Simulation of Electron Transport in Si: The First 20 Years," presented at *European Solid-State Device Research Conference (ESSDERC-96)*, September, 1996.

[3] N. Sano and A. Yoshii, "Impact-Ionization Theory Consistent with a Realistic Band Structure of Silicon," *Phys. Rev. B*, vol. 45, p. 4171, 1992.

[4] K. Taniguchi, *et al.*, *International Electron Device Meeting (IEDM) Technical Digest*, p. 335, 1994.

[5] E. Takeda and N. Suzuki, "An Empirical Model for Device Degradation due to Hot-Carrier Injection," *IEEE Electron Dev. Lett.*, vol. 4, p. 111, 1983.

[6] C. Hu, S. C. Tam, F.-C. Hsu, P. K. Ko, T. Y. Chan, and K. W. Terrill, "Hot-Electron-Induced MOSFET Degradation: Model, Monitor, and Improvement," *IEEE Trans. Electron Dev.*, vol. 32, p. 375, 1985.

[7] N. Sano, M. Tomizawa, and A. Yoshii, "Temperature Dependence of Hot Carrier Effects in Short-Channel Si-MOSFET's," *IEEE Trans. Electron Dev.*, vol. 42, p. 2211, 1995.

[8] N. Sano and A. Yoshii, "Impact-Ionization Rate near Thresholds in Si," *J. Appl. Phys.*, vol. 75, p. 5102, 1994.

[9] M. V. Fischetti, N. Sano, S. E. Laux, and K. Natori, "Full-Band Monte Carlo Simulation of High-Energy Transport and Impact Ionization of Electrons and Holes in Ge, Si, and GaAs," *Proceedings of International Conference on Simulation of Semiconductor Processes and Devices (SISPAD-96)*, p. 43, 1996.

[10] For example, see, A. van der Ziel, *Noise*, Prentice, New York, 1954.