VLSI DESIGN
1998, Vol. 6, Nos. (1–4), pp. 299–302
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Observation of Anomalous Negative Differential Resistance in Diode Breakdown Simulation Using Carrier Temperature Dependent Impact Ionization

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When carrier temperatures are used to model impact ionization with self-consistent cooling effects, anomalous negative differential resistance (NDR) was found in diode breakdown simulation. Possible mechanisms responsible for the NDR are analyzed.

Keywords: device simulation, energy transport, impact ionization, numerical method

In recent years, the drift-diffusion (DD) model has been extended to the energy transport (ET) model and the hydrodynamic (HD) model to account for non-equilibrium effects from the elevated average carrier energy at high fields. Inclusion of electron and hole temperatures as state variables allows transport coefficients such as mobilities and impact ionization rates as functions of the carrier temperatures instead of the local electric field to remove the thermal equilibrium approximation [1]. However, this new parametrization of the transport coefficients has received controversial criticisms. Although much success has been achieved in fitting specific experiment measurements, especially in MOSFET substrate current cases (e.g., [2]), it has also been established that the distribution function, in particular the tail part that determines the impact ionization and MOSFET gate current, is not well characterized by the carrier concentration and average energy alone [3, 4]. Nevertheless, if the impact ionization rates are *chosen* as functions of the carrier temperatures, we report here for the first time an anomalous negative differential resistance (NDR) in a simple pn junction breakdown simulation. Although this NDR is very small in magnitude and only happens at certain choice of parametrization of transport coefficients in the ET and HD models, identification of such numerical behaviors may prevent erroneous interpretations when complex device structures are simulated. Possible mechanisms that can cause this NDR are briefly summarized.

We have chosen a test pn junction diode with $n^+ = 10^{19} cm^{-3}$ and $p = 5 \times 10^{17} cm^{-3}$ to avoid confusing interpretation when significant amount of minority carriers reaches metallurgical contacts. For simplicity, no band-to-band tunneling model is used. The vicinity of the breakdown region in the reverse-bias IV curves, using field and energy dependencies for the mobility μ and the impact ionization rate α, is shown in Fig. 1. The simulation is performed by PISCES-2ET with modified curve tracing techniques [5] to capture NDR. The DD model with $\mu(F)$ and $\alpha(F)$ does not have any NDR region and the breakdown

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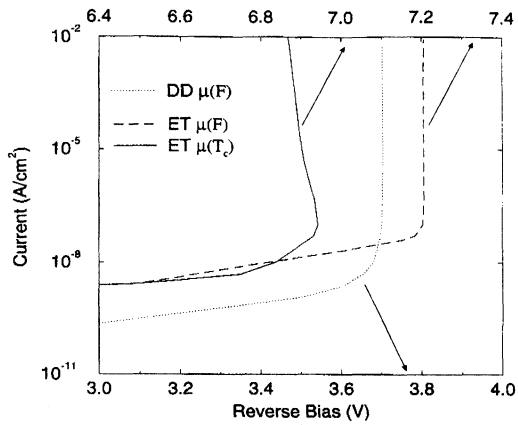

FIGURE 1 Reverse-bias curves for n^+ - p diode breakdown. $n^+ = 10^{19} cm^{-3}$ and $p = 5 \times 10^{17} cm^{-3}$. The drift-diffusion (DD) and the energy transport (ET) models with different mobility models are used

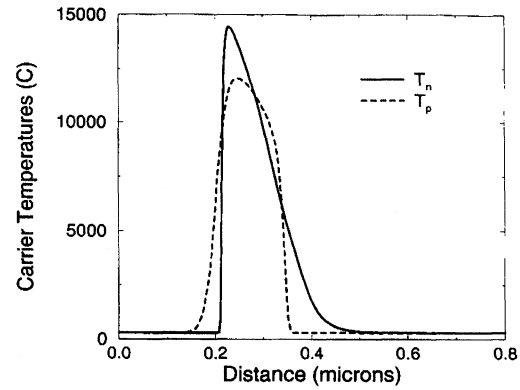

FIGURE 2 Carrier temperature profiles when electrical breakdown happens. Notice that the temperatures are the same at the onset (low current) and deep (high current) breakdown regions. The profiles are those of the ET $\mu(T_c)$ model in Fig. 1

voltage is close to the measured data. At the onset of breakdown, the ET model with $\alpha(T_c)$ and $\mu(T_c)$ shows a small NDR. However, the ET model with $\alpha(T_c)$ and $\mu(F)$, although it is not based on physical reasoning and is only used here as a numerical comparison, does not show any NDR region. There are two possible mechanisms for the observed NDR, and further investigation is necessary to identify which mechanism is more dominant. The first possible mechanism is due to the cooling effect feedback from impact ionization [6]. In the electron (similar for hole) energy balance equation, the energy exchange rate u_{wn} related to impact ionization can be included self-consistently as

$$u_{wn} = g_{n,ii}(E_g + \frac{3}{2}k_B T_p) - g_{p,ii} \cdot \frac{3}{2}k_B T_n \qquad (1)$$

where $g_{n,ii}$ and $g_{p,ii}$ are the impact ionization rates initiated by electrons and holes, E_g is the band gap, and T_n and T_p are the electron and hole temperatures. This cooling gives a positive feedback for enhancement of $\mu(T_c)$, since asymptotically $\mu \propto T_c^{-1}$ for velocity saturation. This small NDR will mostly disappear if $\mu(F)$ is used or the cooling mechanism is not accounted for in the carrier energy balance equation.

The second possible mechanism is bipolar multiplication. When diode breakdown happens, both the electric field and carrier temperatures stop increasing

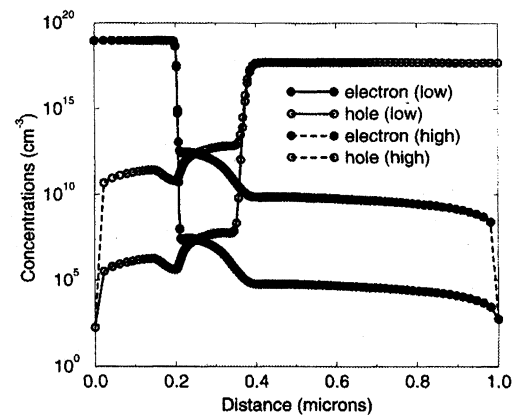

FIGURE 3 Carrier concentration profiles at the onset (low) and deep (high) breakdown regions

(shown in Fig. 2) and the carrier concentrations (shown in Fig. 3) and impact ionization generation rates (shown in Fig. 4) start building up within the *original* depletion region. If $\alpha(F)$ is used, the peak generation rates for electrons and holes are always aligned. However, as can be seen in Figs. 2 and 4, the peaks of $\alpha_n(T_n)$ and $\alpha_p(T_p)$, as well as T_n and T_p, are offset by a small distance [6]. The multiplication fac-

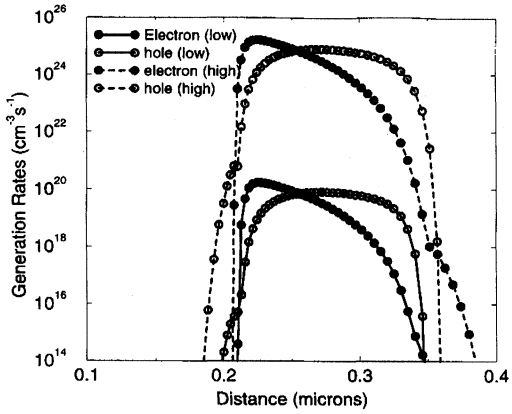

FIGURE 4 Profiles of generation rates initiated by electron and hole impact ionization

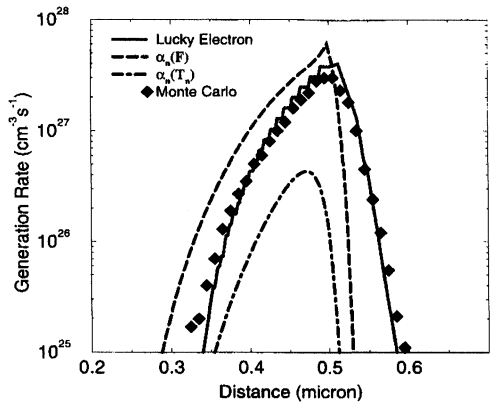

FIGURE 5 The generation rate in 0.4 μm nin device (with $n = 5 \times 10^{17}$) under 6V bias

tor M defined by the ratio of outgoing and incoming electron (or hole) currents in the depletion region can be expressed as [7]:

$$1 - \frac{1}{M} = \int_0^W \alpha_n \exp\left[-\int_x^W (\alpha_n - \alpha_p)dx'\right] dx \qquad (2)$$

If $\alpha_n(x) \equiv \alpha_p(x)$, the breakdown condition as $M \to \infty$ is simply $\int_0^W \alpha = 1$ and no NDR is possible as long as the depletion region remains the same width and a has only one peak of F within it. However, if $\alpha_n(x) \neq \alpha_p(x)$, the reverse breakdown current is affected by the convolution of α_n and α_p, and NDR can exist for slightly perturbed T_n and T_p profiles.

Besides, it can be observed that the breakdown voltage predicted by $\alpha(T_c)$ is much larger than that by $\alpha(F)$[9]. This can be understood from two aspects. First, when only one carrier is considered (as in nin cases of Fig. 5), the generation rate calculated by $\alpha(T_c)$ is smaller than $\alpha(F)$ due to the latent effect from dF/dx (note that in the bulk case, $\alpha(T_c) \equiv \alpha(F)$ by definition). Second, if the peaks of α_n and α_p are dislocated, the integral in (2) will be more damped than when α_n and α_p are aligned.

Acknowledgements

This work is supported by the National Science Foundation (NSF) through the National Center for Computational Electronics (NCCE) grant no. NSFECS-9200560. Main ideas were formulated during the visit of one of the authors (E.C.K.) to the NCCE site at University of Illinois at Urbana-Champaign. The authors also wish to thank Drs. Ke-chih Wu and Lydia So who were previously with Stanford University for many fruitful discussions.

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