Impact-ionization in silicon at large operating temperature

M. Valdinoci, D. Ventura, M.C. Vecchi, M. Rudan, G. Baccarani, F. Illien [a], A. Stricker[a], L. Zullino[b]

Dept. of Electronics, University of Bologna,
viale Risorgimento 2, 40136 Bologna, Italy
[a]Integrated Systems Laboratory, ETH Zurich, Switzerland
[b]ST-Microelectronis, Cornaredo, Italy

Abstract

In this work, electron impact-ionization in silicon is investigated both theoretically and experimentally in the temperature range between 25 and 400°C. A new compact model for the impact-ionization coefficient is proposed, which nicely fits the theoretical data from the Boltzmann solver HARM [1] and the available experimental data in the above temperature range. The new model has been validated by simulating the reverse characteristics of junctions diodes, and turns out to correctly predict the temperature dependence of breakdown voltage.

1. Introduction

Much work was devoted in the past to model and measure the impact-ionization coefficients in silicon. The measurements were predominantly carried out at room and lower temperature, while experimental characterization at large operating temperature are only a few and, to our knowledge, no measurements were carried out above 160°C (e.g., [2] and references therein). Aim of this work is to determine the temperature dependence of the ionization coefficients in an extended temperature range, which is becoming more and more important in association with studies on electrostatic discharge (ESD). A novel compact model for both electron and hole ionization coefficients is worked out for temperatures ranging from 25 to 400°C. The new model, implemented within the device simulator DESSIS [3], has been validated by comparing simulation results with breakdown measurements on bipolar devices, and turned out to nicely predict the breakdown data over the above temperature range.

2. Experimental

A novel setup was specially designed at ETH for measuring semiconductor devices at temperatures up to 550°C. The high-temperature setup comprises a custom-built vacuum-tight tube oven, a motor-driven loading system, and a specially designed sample holder. The sample is contacted through a ceramic substrate used as an interconnect between spring-loaded pins and the micro-chip [4]. The setup proved to

be reliable for reproducible measurements and easy handling.
Structures specially designed for the extraction of the ionization coefficients were fabricated at ST-Microelectronics in BCD3 (Bipolar-CMOS-DMOS) technology [5]. Among these structures, Static Induction Transistors (SIT) and VDMOS, which are suitable for the extraction of the ionization coefficients at relatively-low electric fields, and bipolar transistors, which are more suitable for the extraction of the coefficients at larger electric fields have been designed and manufactured. In Fig. 1 the experimentally-determined electron ionization coefficient is compared with some published data at room temperature. It is clear from the figure that a large spread of values exists in the literature. This is due to the fact that the ionization coefficient strongly depends on the electric field, whose distribution along the current flow lines can hardly be known with high precision. In this work, the field distribution is determined by process and device simulation. Also, the test structures have been carefully designed in order to ensure a one-dimensional electric field distribution in the device active region. So doing, the use of calibrated vertical impurity profiles ensures the required accuracy on the electric field. The data extracted from the test structures agree with those given by Lee and Sze [6], and by Takayanagi *et al.* [7], for electric fields ranging from 130 to 170 kV/cm. Discrepancies exist instead in the lower-field range.

3. Results and discussion.

High-temperature impact-ionization was first investigated by means of the Boltzmann solver HARM [1], which provides the energy distribution function of the carriers within the silicon material in a wide range of temperatures and fields. By implementing within the Boltzmann solver the most important scattering mechanisms which affect the carrier-distribution function, namely impact-ionization, acoustic and optical phonon scattering and impurity scattering, the solver provides an accurate prediction of the impact-ionization coefficients within the explored temperatures. The results of the Boltzmann solver are approximated by an empirical function suitable for implementation within device simulators, and the related parameters are extracted. The impact-ionization analytical model reads

$$\alpha = \frac{F}{a(T) + b(T)\exp\left[d(T)/(F + c(T))\right]} \tag{1}$$

where F is the electric field along the current flow lines. The same expression holds for both electrons and holes. The parameters in (1) depend on temperature as follows:

$$\begin{aligned} a(T) &= a_0 + a_1 T^{a_2} \\ b(T) &= b_0 \exp(b_1 T) \end{aligned} \tag{2}$$

$$\begin{aligned} c(T) &= c_0 + c_1 T^{c_2} + c_3 T^2 \\ d(T) &= d_0 + d_1 T + d_2 T^2 \end{aligned} \tag{3}$$

The parameters for both electrons and holes are given in Table 1.
The analytical model nicely fits the predictions of the numerical model inherent in HARM for electric fields ranging from 50 kV/cm to 500 kV/cm. It also provides a

Parameters	Electrons	Holes
a_0	4.3383	2.376
a_1	-2.42×10^{-12}	0.01033
a_2	4.1233	1
b_0	0.235	0.17714
b_1	0	-0.002178
c_0	1.6831×10^4	0
c_1	4.3796	0.00947
c_2	1	2.4924
c_3	0.13005	0
d_0	1.233735×10^6	1.4043×10^6
d_1	1.2039×10^3	2.9744×10^3
d_2	0.56703	1.4829

Table 1: Model parameters.

good agreement with the impact-ionization coefficient extracted from experimental data in the electric-field range from 130 to 230 kV/cm. The new model is compared in Fig. 2 with the experimental data for temperatures up to 400°C, and a generally-good agreement is obtained. The temperature-dependence of the existing impact-ionization models implemented in commercially-available device simulators is derived from the theory by Crowell and Sze [8], which is known to provide an incorrect temperature behavior of the breakdown voltage in *p-n* junctions. The electric-field dependence of the new compact model for electrons is compared in Fig. 3 with Chynoweth's model [9] with temperature-dependent parameters, according to the theory developed by Crowell and Sze. In the above figure, the continuous and dashed lines represent the Chynoweth model with room-temperature parameters values from Van Overstraeten [2], while symbols represent the new model. One can observe that the theory by Crowell and Sze predicts a much stronger temperature dependence for α_n than the new model we propose. Similar results hold for holes. The model was implemented within the DESSIS code, and validated via simulation of suitable test-structures. As an example, the breakdown voltage of a p^+/n-well diode is reported in Fig. 4 as a function of temperature. In the same figure, simulation results using the new impact-ionization model are compared with Van Overstraeten and Lackner [10] models. It can be seen that the weaker temperature dependence of the impact-ionization coefficient allows us to nicely fit the experimental data.

Acknowledgments

This work has been supported by the EU ESPRIT-Project 23643 ESDEM. The measurement support by Dr. Wladek Grabinsky is gratefully acknowledged

References

[1] M. C. Vecchi *et al.*, *IEEE-TED*, 45, n. 1, p. 230, 1998

[2] W. Maes *et al.*, *Solid-State Electronics*, 33, 6, p. 705, 1990

[3] ISE Integrated Systems Engineering AG, sl ISE TCAD Manuals, V. 5.0, 1998

[4] W. Grabinsky *et al.*, *4th HiTECH Conference Proc.*, 1998

[5] A. Andreini, *IEEE Transaction on Electron Devices,*, ED-33,12,p.2025, 1986

[6] A. Lee *et al.*, *Physical Review A* 134, p. 761, 1964

[7] I. Takayanagi *et al.*, *Journal of Applied Physics* 72, 5, 1992

[8] C. R. Crowell *et al.*, *Applied Physics Letters* 9, 6, p. 242, 1966

[9] A. G. Chynoweth, *Physical Review* 109, p. 1537, 1958

[10] T. Lackner, *Solid-State Electronics* 34, 1, p. 33, 1991

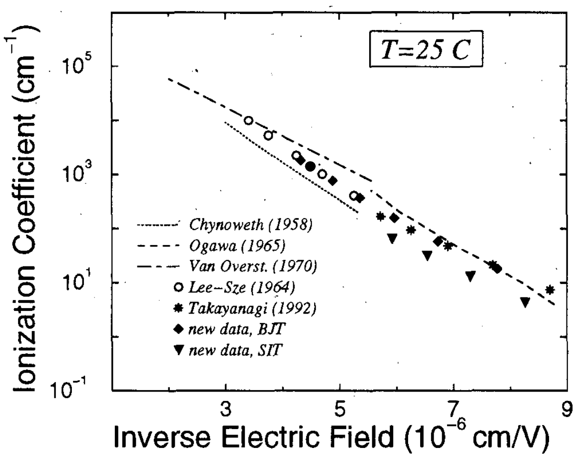

Fig. 1: Electron ionization coefficient vs. inverse electric field at different temperatures: comparison with literature data.

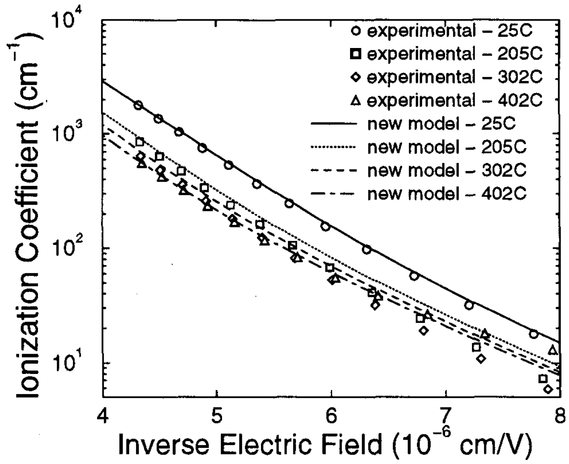

Fig. 2: Electron ionization coefficient: experimental data (symbols) compared with the new impact-ionization model (continuous lines).

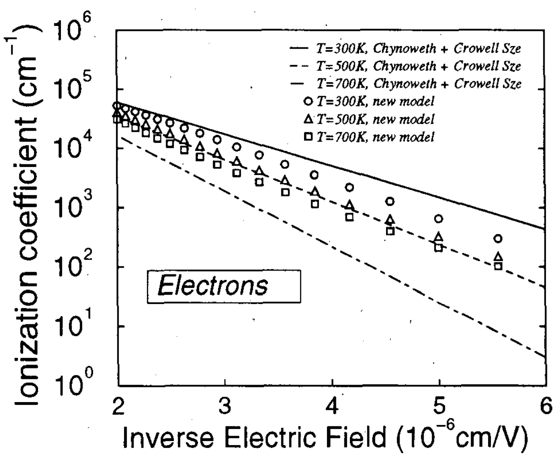

Fig. 3: Electron ionization coefficient calculated with the present model and Chynoweth's (dashed lines).

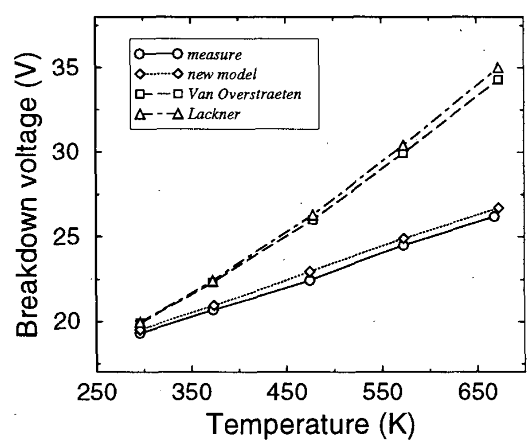

Fig. 4: Breakdown voltage of Pplus/nwell diode vs. temperature: comparison between experimental data and simulation results.