Improved impact-ionization modelling and validation with pn-junction diodes

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***Abstract*— Impact-ionization at low and high electric field as well as the temperature dependence has to be modeled well in order to improve the predictive capability of TCAD tools. The high field behavior is of particular interest for ESD protection devices with low breakdown voltages which are used to protect ICs made with modern technologies. In this paper, the model for estimating the impact-ionization proposed by Valdinoci [1] with the parameters of Reggiani [2] has been examined with diodes of various breakdown voltages. It was found that the experimental breakdown voltages of the diodes are underestimated using that model. The cause was traced back to the overestimation of the electron impact-ionization coefficient at high electric fields. By adjusting the model parameters to the experiments of Van Overstraeten [3] and Grant [4], who measured the impact-ionization coefficient in silicon for fields up to 7.7 × 10^5 V/cm, we extend the model's validity to high fields. With the new parameter set, a much better agreement to the measured breakdown voltages is obtained. As a check for the temperature dependence of the impact-ionization, the diodes were further investigated under 100 ns transmission line pulses (TLP). The measured high-current I-V characteristic is well reproduced by simulations using the new model, as opposed to the well-established model based on Chynoweth's law. Both the failure level and the damage location are well predicted by the simulation.**

I. INTRODUCTION

Impact-ionization plays an important role in semiconductor devices. As the width and the gate oxide thickness of ICs continue to scale down, the need for electrostatic discharge (ESD) protection devices with low breakdown voltages are becoming more important. Also, due to the high current injection condition, local temperatures inside semiconductor devices during an ESD event can become very high. In order to simulate the behavior of ESD protection devices, the impact-ionization model has to be valid in a wide range of electric fields and high temperatures. Much work devoted in the past to model the impact-ionization coefficient of carriers in silicon uses an empirical formula first proposed by Chynoweth [5]. However, no measurements were carried out at higher temperatures. Reggiani et al. [6] investigated the transport properties of carriers numerically using the spherical-harmonics expansion (SHE) method. Based on the numerical data, a new compact impact-ionization model was proposed to approximate the SHE data [1], and the model was validated by comparing simulated breakdown voltages of diodes with measured ones in the range of 300 to 673 K. Since then, the model has been intensively studied both theoretically and experimentally [7] [8]. It was shown that the impact-ionization coefficient deviates from the Chynoweth's law under high temperatures because of the non-equilibrium Auger generation, which is not considered in the Chynoweth-like models. The model proposed by Valdinoci was improved further to fit experimental data for temperatures up to 773 K and electric fields up to 3.5 × 10^5 V/cm [2]. In low breakdown voltage devices, however, the electric field can easily exceed this value and we found that the model underestimates the breakdown voltages of such devices. This paper aims at extending the validity range of Valdinoci's impact-ionization model to higher electric fields and is organized as follows: in section II, the fabricated diodes are described. In section III, the simulated breakdown voltages are compared to the measurements. The error of the simulation is investigated, and a new set of parameters is proposed. In section IV, it is shown that the behavior of the diodes under ESD condition can be well reproduced with simulations using the improved model.

II. DEVICE FABRICATION

In this work, we simulated and measured avalanche diodes with various breakdown voltages, which are fabricated by NXP with standard vertical Zener processes. The schematic cross-sections of the devices are shown in Fig. 1. The breakdown voltages of the fabricated devices range from 6.8 to 70 V. To optimize the simulation input, doping profiles in the active region of the diodes have been determined by SIMS and used in device simulation. Fig. 2 shows the measured SIMS profiles of two diodes.

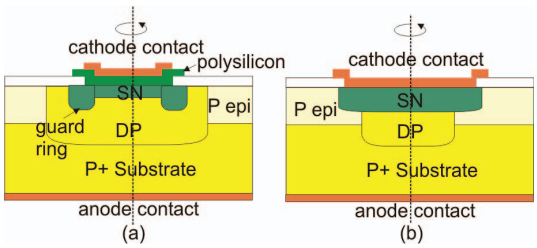

Figure 1. Schematic cross-sections of the vertical diodes with breakdown voltages (a) up to 27 V, and (b) from 7.5 V to 70 V. All the devices are cylindrically symmetrical around the axis shown in the figure.

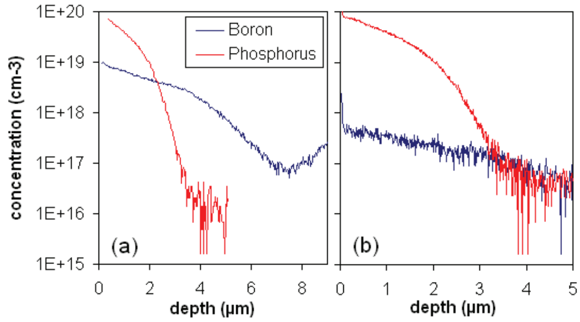

Figure 2. SIMS measurements of the doping profiles in the active region of two diodes with (a) 8 V breakdown voltage, (b) 27 V breakdown voltage.

III. Results And Discussion

The breakdown voltages of the diodes were simulated with the Chynoweth model using parameters of Van Overstraeten [3], and the Valdinoci model [1] as shown in (1) using parameters of Reggiani [2] with the commercial 2-D device simulation tool Medici.

$$\alpha(E,T)=\frac{E}{a+b\exp[g(E,T)]}$$

$$g(E,T)=\frac{d_0+d_1\cdot T/300}{c_0+c_1\cdot T/300+c_2\cdot(T/300)^2+E} \qquad (1)$$

The simulated values of breakdown voltage are plotted against the measured ones in Fig. 3. It can be seen that with Van Overstraeten's parameters, the simulated breakdown voltages are in good agreement with the measurements. Unfortunately, with the Valdinoci model the breakdown voltages, especially for diodes with low breakdown voltages, are underestimated. The maximum error can be as much as 25%.

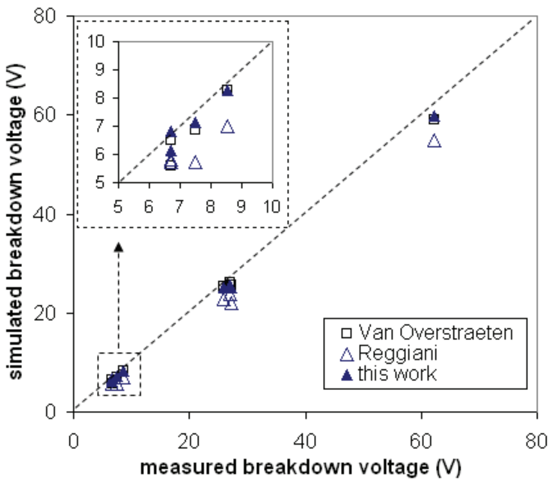

Figure 3. Comparison of measured and simulated breakdown voltages of various diodes using model parameters of Van Overstraeten and of Reggiani. Adjustment of Reggiani's parameters leads to a much better fit (this work).

Further investigation of the simulation results revealed that the electric fields occurring in the low breakdown devices exceed the validity range of the Valdinoci model. For diodes with breakdown voltages below 8.0 V, the maximum electric field at the reverse biased pn-junction is above 8×10^5 V/cm according to the Medici simulation.

Impact-ionization coefficient measurements in silicon at high electric fields have been independently carried out by Van Overstraeten [3] ($1.75\times10^5 < E < 6.0\times10^5$ V/cm) and Grant [4] ($2.0\times10^5 < E < 7.7\times10^5$ V/cm). As shown in Fig. 4, the values obtained from the model with Reggiani's parameters deviate from these measurements significantly when the electric field is above 5×10^5 V/cm. The deviation is especially obvious when one plots the impact-ionization coefficient against the electric field (see Fig. 4 (b)), instead of the inverse electric field, which is traditionally done.

To correct this mismatch, the parameters a and b in (1) are adapted as shown in Table I. It should be noted that the temperature dependence of the function *g(E,T)* is not changed. After adapting the model, the electron impact-ionization coefficient agrees very well with Van Overstraeten and Grant's measurements at high-field (Fig. 4 (b)). The new parameter set extends the validity range of the Valdinoci model to electric fields up to approximately 8×10^5 V/cm. It is worthwhile to point out that the adjusted model is supposed to be valid for silicon in general, as the applicability of Van Overstraeten and Grant's results is not restricted to a particular device.

TABLE I. Original and Adjusted Parameter Values for the Electron Impact-Ionization Coefficient

Parameter	Original value	Adjusted value	Unit
a	2.2	4.5	V
b	0.14	0.182	V

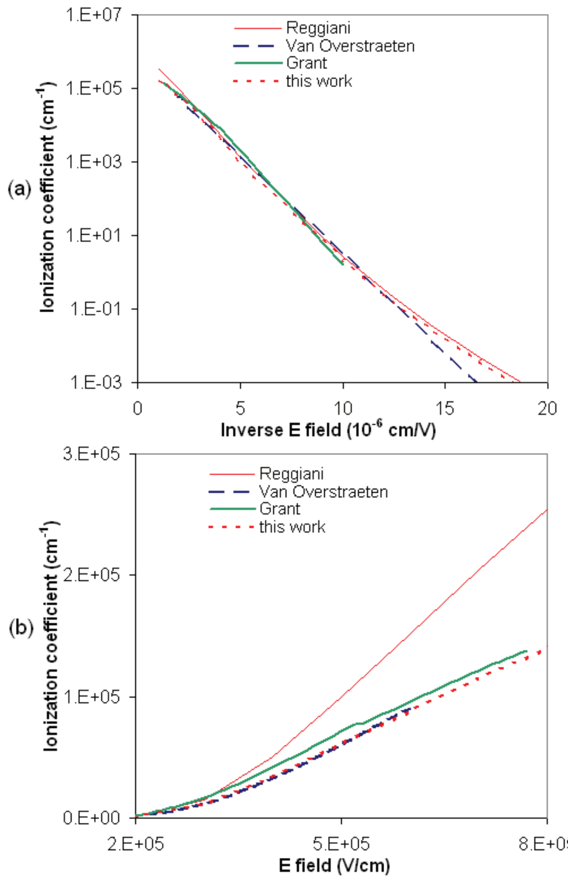

Figure 4. Electron impact-ionization coefficient (a) as a function of the inverse electric field and (b) the electriec field at T = 300 K.

The simulated breakdown voltages of all the diodes now fit to the measurements with a maximum error of 8%, as shown in Fig. 3.

In the following, some justifications are given concerning the adjustments of the parameters. First of all, it was experimentally observed by Grant that the impact-ionization coefficient starts to deviate from Chynoweth's law at high fields and the measured data lie below the empirical curve [4]. In order to account for the difference between measurements and the empirical model, Grant proposed to use different sets of parameters for the Chynoweth model in high-field and low-field regions. Valdinoci, on the other hand, tried to account for that effect by adding the parameter a to the exponential in the first part of (1). The effect of a is negligible in the low-field region, however, it allows the impact-ionization coefficient to become linearly dependent on the electric field at high-field regions. Fig. 4 (b) clearly shows that the high-field behavior of the impact-ionization is overestimated by Reggiani's parameters.

Secondly, the parameter b is a multiplicative factor to the exponential $exp[g(E,T)]$. Its value influences the onset of the transition to the high-field region, when the product $b \cdot exp[g(E,T)]$ becomes comparable to a. In this work, b is adjusted to fit the curve better to measurements of Van Overstraeten and Grant. The impact-ionization coefficient in the low-field region is also slightly reduced by the adjustment, however, the shift is minimal compared to the scattering of various experimental data [2] and the fit in the low-field region is still very good.

Finally, it is noted that the most relevant temperature variation, which appears in the exponent $g(E,T)$, is not changed. Therefore, the temperature dependence of the impact-ionization which fits well to Reggiani's measurements is obtained as illustrated in Fig. 5.

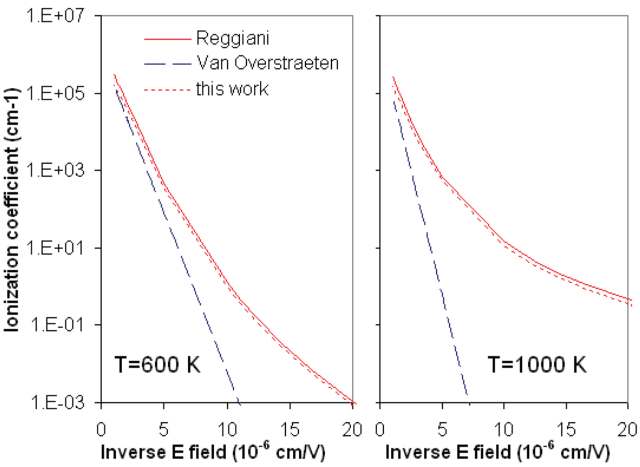

Figure 5. Electron impact-ionization coefficient as a function of the inverse electric field at 600 K (left) and 1000 K (right). Comparison between the models of Reggiani, Van Overstraeten and this work.

IV. ESD Measurements And Simulations

In order to examine the predictive capability of the impact-ionization models, the high-current I-V characteristic of different diodes was measured with 100 ns transmission line pulses (TLP), and TLP simulations were done using the electro-thermal model in Medici. Fig. 6 shows both the simulated and measured I-V characteristic of two diodes. The I-V curve and the failure level for both diodes are well reproduced by simulations. Fig. 7 shows the transient voltages on the cathode of diode A at a current level (6 A) just before the device is destroyed. The Valdinoci model gives a much better fit than Van Overstraeten's model, and the simulated curves fit well to measurements even when the peak temperature inside the device exceeds 773 K.

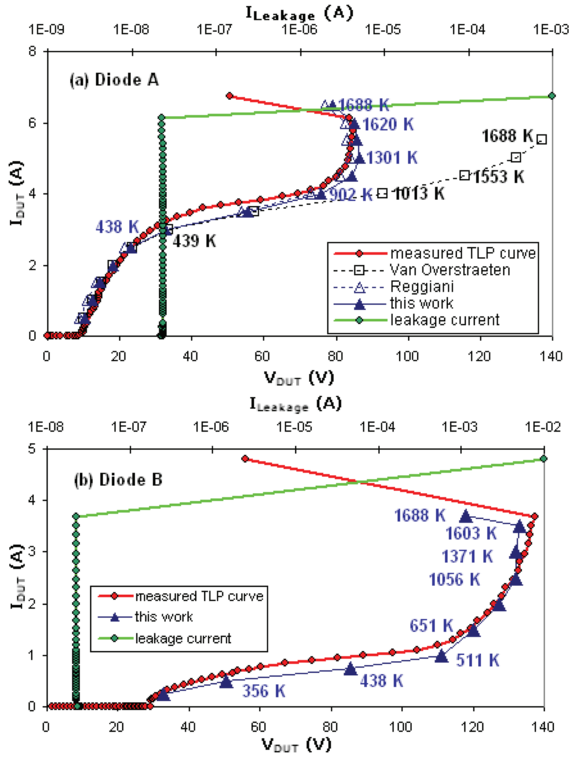

Figure 6. Measured and simulated TLP curves for two diodes with different breakdown voltages. Measured leakage currents indicate the failure level of both devices. The peak temperature during a TLP pulse simulation is given in the labels. For diode A, Van Overstraeten's model has been used in the simulations for comparison.

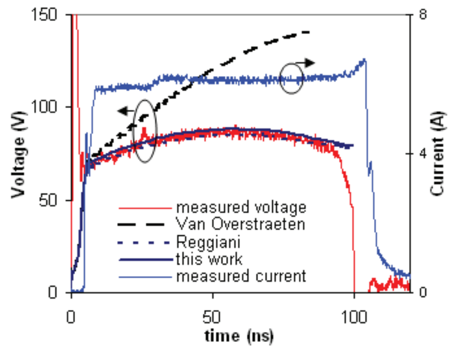

Figure 7. Measured current and voltage waveforms of a 100 ns pulse on the cathode of diode A. The transient voltages on the cathode during the TLP pulse are simulated with different models.

It is observed from the simulation that once the current level is high enough and the conductivity modulation occurs, the electric field starts to extend from the pn-junction to the epi/substrate junction until finally a second avalanche region is formed there. Once the current level approaches the destruction level, the local lattice temperature is so high at the end of the pulse that thermal generation of carriers becomes comparable to the impact-ionization. Therefore, less electric field is needed to create carriers, which is reflected by a reduction in the voltages as shown in Fig. 7. Finally, current constriction is seen to develop in the simulation, which increases the local temperature rapidly above the melting temperature of silicon. This is supported by the physical failure analysis done at damaged devices. The local ESD damage is thought to be caused by a vertical current filament. The location of the ESD damage area matches very well to the position of the hotspot in the simulation as shown in Fig. 8.

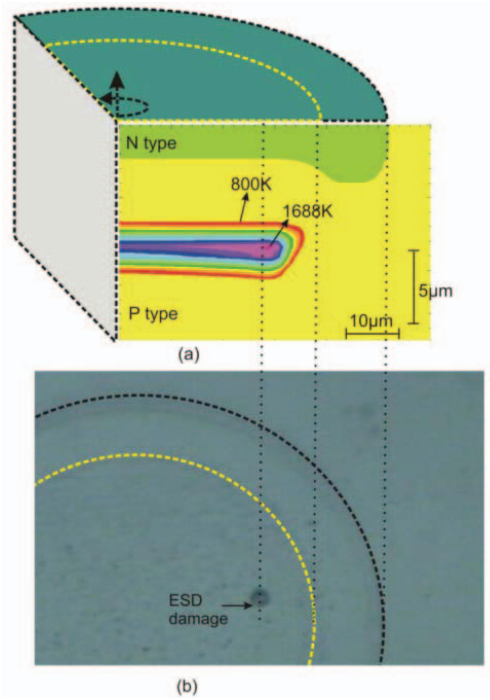

Figure 8. (a) Simulated 2-D doping regions and the lattice temperature distribution at the end of a 100 ns TLP pulse (I = 6.5 A) of diode A. (b) ESD damage visible at the silicon surface of a destroyed device after removal of the passivation and the metal layers.

V. Conclusions

The validity range of the Valdinoci impact-ionization model has been be extended to electric fields up to 8×10^5 V/cm by adjusting two parameters. The model was used to reproduce the measured breakdown voltages of various diodes, and the improved parameter set was found to be crucial for the correct simulation of devices with low breakdown voltage. In contrast to previous models based on Chynoweth's law, the high-current TLP characteristics and the failure level of various diodes can be well predicted by simulations. The correct simulation of the transient voltages on the diodes during a TLP pulse and the good match between physical failure analysis and the hotspot in the simulation seem to suggest that the model is also valid above 1200 K, even though it was only validated up to 773 K.

With the improved model, it becomes possible to simulate silicon devices with impact-ionization at high electric fields. The improvement allows designers using device simulation to predict the most important parameters of ESD protection devices, such as the breakdown voltages, holding voltages, hotspot location, failure level, etc.

Acknowledgment

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