Nonlinear Contact Resistance and Inhomogeneous Current Distribution at Ohmic Contacts

D. Schröder, T. Ostermann, and O. Kalz

Technische Elektronik, TU Hamburg-Harburg
Eißendorfer Straße 38, D-21073 Hamburg, GERMANY

Abstract

Results of simulations are presented that make use of a recently proposed model for non-ideal ohmic contacts. The model considers both tunneling and thermionic emission currents across the contact. The nonlinearity of the contact resistance is discussed. The two-dimensional current distribution under the contact arising from doping variations is investigated. It is shown that slight doping variations can result in strong current inhomogenities.

1. Introduction

In [1], [2], a model of non-ideal metal-semiconductor contacts for semiconductor device simulation has been proposed. The model considers both tunneling and thermionic emission currents across the contact and allows the simulation of contacts on very low to very highly doped material with a single model. In this paper, we investigate the properties of the model for the case of nearly-ohmic contacts by applying it in actual device simulations.

The paper is organized as follows. In section 2, some details of the implementation are given. In section 3, we compute the current-voltage characteristics of the contact for various doping concentrations and compare them to the usual model of ideal contacts. The nonlinearity of the contact resistance is discussed. In section 4, we investigate the current distribution under the contact in a two-dimensional simulation. In particular, the current distributions at an ideal and a non-ideal contact are compared. Finally, we investigate the change of the current distribution with respect to a slight variation of the doping concentration under the contact.

2. Implementation of the contact model

We implemented a simplified version of the model for nearly ohmic contacts into the device simulator PARDESIM [3], [4]. The model assumptions are 1) charge neutrality on the boundary, 2) tunneling and thermionic emission current of the majority carriers according to [1], and 3) Fermi level continuity across the contact for the minority carriers [5]. These assumptions are used as boundary conditions for the Poisson equation and for the electron and hole continuity equations, respectively. Assumption 1) corresponds to the special case that the tunneling length comprises the total depletion region of the interface [2]. This is only the case if the depletion region is very thin, i.e. if the doping is high. Thus, the model is valid for ohmic contacts. Assumption 2) leads to a finite quasi-Fermi energy step across the contact, and thus to a nonzero specific contact resistance [1]. The well-known ideal contact model differs only in assumption 2) by assuming instead continuous Fermi energy across the contact also for the majority carriers.

Simulations have been carried out for Al contacts on n-Si (0.7 eV barrier height). Since the semiconductor is mostly in degeneration in the considered doping range, we used for the simulations a simplified version of the heavy-doping transport model as described in [6]. Briefly, this model accounts for heavy-doping effects by using a doping-dependent apparent bandgap narrowing.

3. Nonlinearity of the contact resistance

First, we tested the model with a one-dimensional simulation of a resistor, consisting of a bar of homogeneous n-semiconductor with length $L = 6\mu m$. The resistor has an ideal ohmic contact at $x = L$, and a non-ideal contact at $x = 0$ [4]. Fig. 1 shows the current-voltage relationship of the resistor for various doping concentrations.

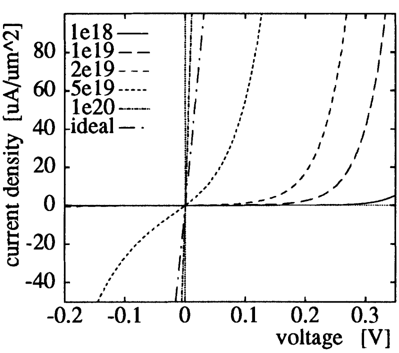

Figure 1:
IV characteristics (large scale)

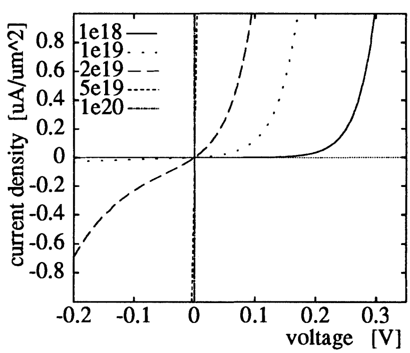

Figure 2:
IV characteristics (small scale)

We see a linear behaviour for a doping of $10^{20}\,cm^{-3}$. At lower doping concentrations the curves become nonlinear, thus indicating the non-ideal behaviour of the contact in these cases. The physical reason is that the tunneling probability is strongly sensitive to variations of the electron Fermi level drop across the contact [1]. We found that the applied bias dropped almost entirely across the non-ideal contact, indicating that its resistance is much larger than that of the semiconductor bulk.

For comparison, the line for a $10^{18}\,cm^{-3}$ doped resistor with two *ideal* ohmic contacts is displayed in Fig. 1, too. We note large differences between the devices with the ideal and non-ideal contacts. The slope of the line in the ideal contact case is inversely proportional to the resistance of the semiconductor bulk, since the ideal contact has zero resistance.

Fig. 2 shows the same plot as Fig. 1, but on a much smaller current density scale. It is interesting to note that the character of the curves depends on the scale. While the $5 \cdot 10^{19}\,cm^{-3}$ curve in Fig. 1 appears nonlinear, it looks like a nearly ideal contact in Fig. 2. The $2 \cdot 10^{19}\,cm^{-3}$ curve in Fig. 1 shows a rectifying behaviour, while on the smaller scale it looks like a nonlinear resistor. From this observation we conclude that the ideal or non-ideal appearance of a contact depends on the magnitude of the current density flowing through the contact, which might not be determined by the contact alone but also by depletion regions etc. inside the device. Thus it depends on the particular operating conditions if the use of an ideal contact model, a current independent contact resistance, or the non-ideal model is appropriate.

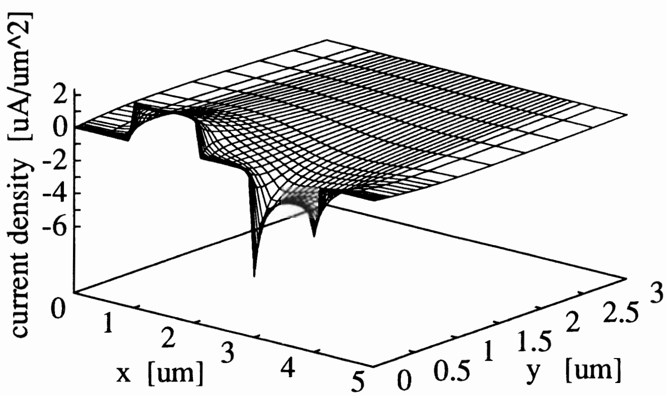

Figure 3: y-component of electron current density

4. Current distribution under the contact

In a second example, we investigated the current density distribution obtained in a two-dimensional simulation [4]. The simulated device was a $5\mu m \times 3\mu m$ piece of silicon with two planar contacts of $1\mu m$ length and a constant doping of $10^{19}\,\mathrm{cm}^{-3}$. Fig. 3 shows the distribution of the y-component of the electron current density at a bias of 0.2 V. The non-ideal contact ($x = 1..2\mu m$) has a smooth current distribution, while the ideal contact model at $x = 3..4\mu m$ exhibits sharp current density peaks at the ends of the contact. The reason for the latter effect is that the ideal contact model demands constant Fermi levels and potential and thus effectively "shortcuts" the semiconductor. Hence, the electrons leave the metal predominantly at the ends of the contact. The contact resistance of the non-ideal contact, on the contrary, ensures a uniform distribution of the current density. We found that the uniform distribution in this example is nearly unaffected by the magnitude of the bias or the electric field near the contact. Thus, the use of a position independent contact resistance is justified as long as the doping under the contact does not change.

In order to investigate the influence of doping variations on the contact resistance, we introduced a slight increase of the doping concentration in the region near the non-ideal contact. Fig. 4 shows that the doping in the contact plane now varies from $4 \cdot 10^{19}\,\mathrm{cm}^{-3}$ to $\approx 2 \cdot 10^{19}\,\mathrm{cm}^{-3}$. In Fig. 5 we can see that this slight doping variation causes a significant reduction of the current density under that portion of the contact where the doping is lower. While the doping drops by a factor of two, the current density drops by a factor of 10. In other words, the effective contact size reduces to ca. 75% of the original metallization size. As apparent from Fig. 1, this effect is due to the drastic sensitivity of the contact resistance to the doping concentration. Thus, the slight doping variation of Fig. 4 leads to a strong inhomogenity of the specific contact resistance, and a correspondingly inhomogeneous current distribution. A simple estimation of the contact current density from the total current and the contact area might underestimate the peak current density in such cases. For simulations where the current distribution near the contacts is important, it can be expected that the non-ideal model would give more satisfactory results.

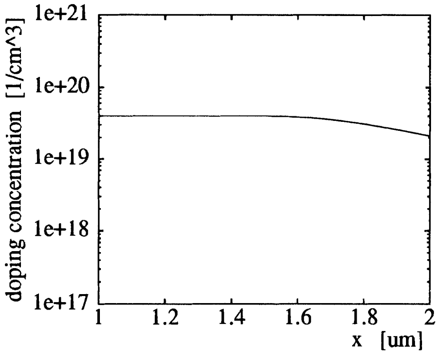

Figure 4:
Doping distribution under contact

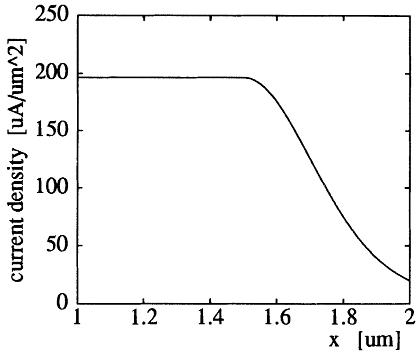

Figure 5:
Normal current density under contact

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