Effect of the surface recombination and the depletion region on the electron beam induced current at a Schottky nanocontact

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Abstract: An analysis of the depletion region that is induced in a semiconductor by a circular nano Schottky contact perpendicular to the electron beam is presented. The electron beam induced current (EBIC) collection efficiency η was calculated using a Monte Carlo simulation (MCS) approach. The nano Schottky of radius r_c is surrounded by a zero or an infinite surface recombination velocity ($v_s = 0$ or $v_s = \infty$). The depletion region of the contact has a hemispherical form of radius z_D. The EBIC was obtained by simulating the random diffusion and collection of the minority carriers that are generated at point-like sources S_i randomly distributed within the generation volume. The profile of the EBIC collection efficiency versus the distance to the nanocontact is obtained. The results show that the values obtained for $v_s = 0$ are greater than those obtained for $v_s = \infty$ and increase with the increase of z_D.

Keywords: electron beam induced current; EBIC; nanocontact; Monte Carlo simulation; MCS; surface recombination; depletion region.

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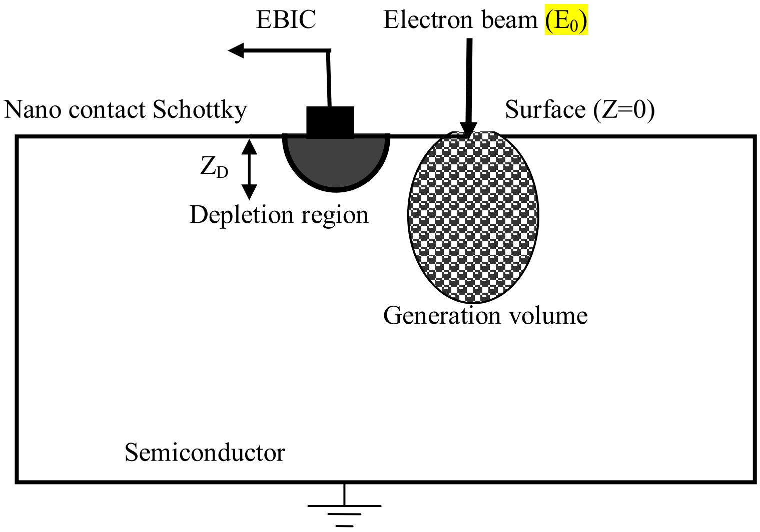
1 Introduction

The scanning electron microscope (SEM) in the charge-collection mode EBIC has been extensively used to characterise the electrical properties of semiconductors. Electrical activity of defects such as grain boundaries and dislocations can be imaged using this technique (Donolato, 1978; Akamatsu et al., 1981; Leamy, 1982; Holt and Joy, 1989; Tabet and Ledra, 1996; Tabet, 1998; Ledra and Tabet, 2005). As the size of semiconductor devices scales down, the traditional analysis of metal semiconductor becomes inadequate and was typically handled by numerical methods. For instance, the EBIC of nano Schottky contacts can be recognised by Monte Carlo simulation (Ledra and Tabet, 2009a, 2009b), but in these works the effect of nano Schottky contact depletion region has been neglected. Recently a very interesting work (Doan et al., 2011) takes into account the shape and the size of this depletion zone, and also some other parameters as the influence of the electron beam energy, the bulk diffusion length and the two limiting cases of the surface recombination velocity infinite and zero. The tilt angle of the electron-beam with respect to the sample surface is equal to 60° (value corresponding to their experimental setup).

In this work, we analyse the effect of the depletion region on the EBIC collection efficiency in the case of a perpendicular electron beam. The nano Schottky contact is described as a circular disc of radius r_c perpendicular to the incident electron beam. The thin metallic film of the contact has been neglected. The surface area around the metallic contact was assumed to be a zero or an infinite surface recombination velocity (v_s = 0 or ∞). The depletion region that is induced in a semiconductor by a circular Schottky contact has a hemispherical form of radius z_D (Figure 1). The EBIC collection efficiency was obtained by simulating the random diffusion and collection of the minority carriers that are generated at point-like sources randomly distributed within the generation volume.

Figure 1 Schematic of the depletion region analysis (see online version for colours)



2 Monte Carlo algorithm

In the first step, our algorithm simulates the electron trajectories and the energy dissipation within the semiconductor, the generation function was obtained in the form of a three dimensional distribution of pointlike sources S_i localised at the middle of the path between two successive primary electron collisions (Tabet and Ledra, 1996; Tabet, 1998). In the second step, our algorithm simulates the random diffusion and collection of the minority carriers that originate from S_i. The random diffusion of the minority carriers emitted from each pointlike source S_i was simulated by considering successive small steps of constant duration Δt. The time interval Δt was taken as a small fraction of the minority carrier lifetime τ (Ledra and Tabet, 2009a, 2009b):

$$\Delta t = \frac{\tau}{N} \tag{1}$$

where N was given typical value ranging from 100 to 10,000 without significant impact on the simulated current. During the time Δt, the carrier crosses a distance ΔS given:

$$\Delta S = \sqrt{D \cdot \Delta t} \tag{2}$$

D is the diffusion constant of the minority carrier.

The scattering direction can be characterised using spherical coordinates (Ledra and Tabet, 2009a). The minority carrier that originates from S_i was considered as collected if it reaches the nano Schottky contact depletion region. It was considered as recombined in the volume after a large number, of diffusion steps ($N_t \geq N$). For infinite recombination velocity v_s the carrier is assumed recombined if it reaches the surface area around the metallic contact or goes outside it. In the case of $v_s = 0$, the carrier reaching or crossing the surface around the metallic contact is 'forced' to diffuse along a trajectory within the surface or towards the bulk of the sample. For each position x_{cb} of incident primary electron beam, the simulated EBIC collection efficiency η^{mcs} (x_{cb}) was calculated as following:

$$\eta^{mcs}\left(x_{cb}\right) = \frac{\sum_{i=1}^{N_S} N_{ci}}{\sum_{i=1}^{N_S} N_{gi}} \tag{3}$$

N_{ci} and N_{gi} are respectively the number of collected and generated minority carriers for each source S_i. The parameter N_S is the total number of sources S_i. The diffusion/recombination process is simulated for a maximum number N_t of steps ΔS. The parameter N_t is adjusted by carrying successive simulations of the EBIC collection efficiency of an infinite Schottky contact perpendicular to the electron beam until it coincides with the theoretical value.

3 Results and discussion

All computations were carried out for silicon sample, E_0 = 5 keV, r_c = 100 nm and L = 1,000 nm. We have carried out computations to establish the profile of the EBIC collection efficiency versus the distance x_{cb} to the centre of the nanocontact for r_c = 100 nm, z_D = 200 nm and two extreme values of the free surface recombination velocity ($v_s = 0$ and $v_s = \infty$), the results are displayed on Figure 2. It is shown that the values corresponding to $v_s = 0$ are greater than those obtained for $v_s = \infty$. At 5 keV incident energy, the lateral extension of the generation volume does not exceed 400nm, consequently a significant fraction of the generated carriers that diffuse outside the generation volume have a possibility to achieve the free surface, hence the observed difference between the values obtained for $v_s = 0$ and $v_s = \infty$.

We have investigated the variation of the profile of the EBIC collection efficiency for different values of the depletion region radius z_D. The results are reported on the Figure 3. It can be observed that the collected current increases significantly as the radius z_D increases. This result is logically expected since the probability that carriers are collected increases with this parameter (Doan et al., 2011). It can also be observed that this figure shows a symmetrical profile, as expected, the maximum of the EBIC efficiency being localised at the nano contact centre. We also observe that in the case of an infinite surface recombination velocity ($v_s = \infty$), the value of the full-width at half-maximum (FWHM) is approximately equal to the diameter of the depletion region (FWHM = z_D = 400 nm).

Figure 2 EBIC collection efficiency profiles of a nano Schottky contact of radius r_c = 100 nm in a silicon sample at 5 keV for z_D = 200 nm and two extreme values of the free surface recombination velocity (v_s = 0 and $v_s = \infty$) (see online version for colours)

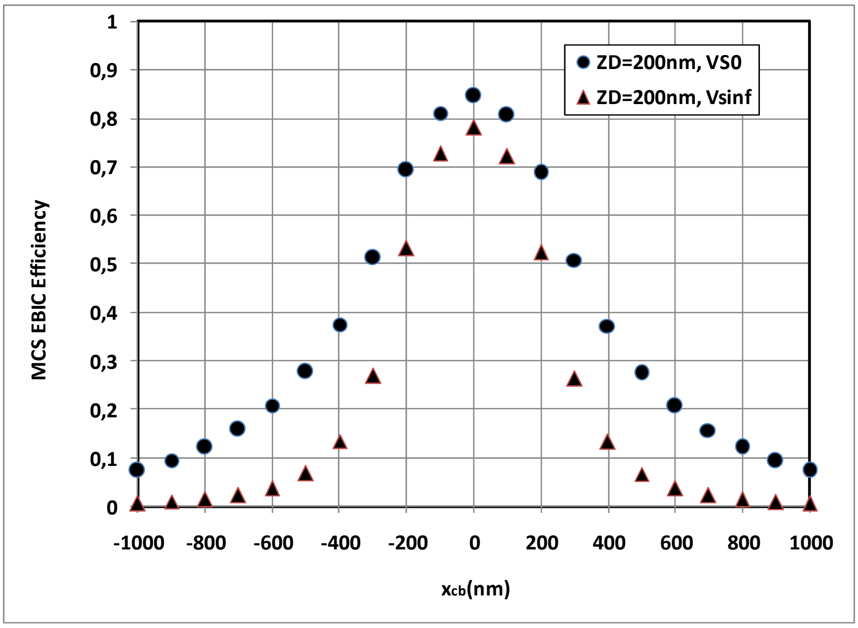
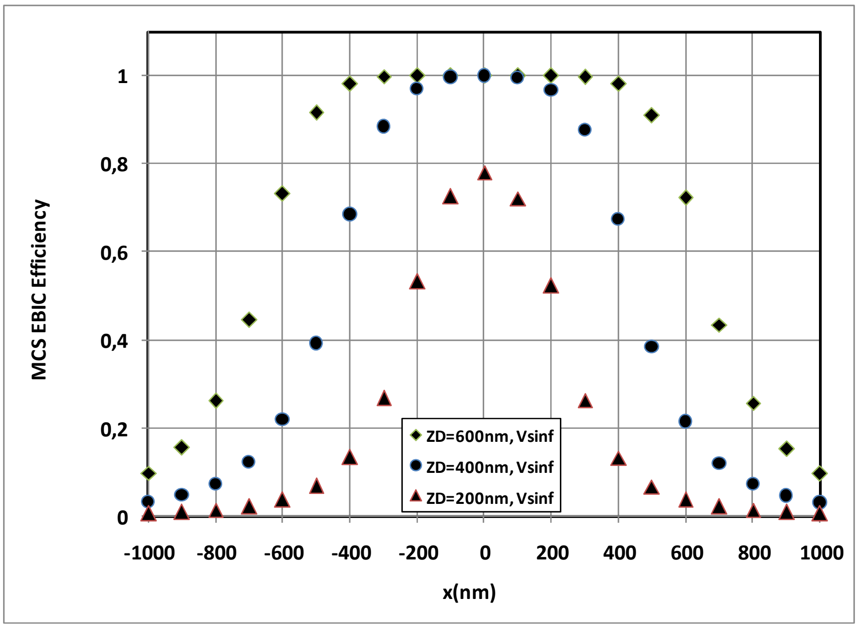
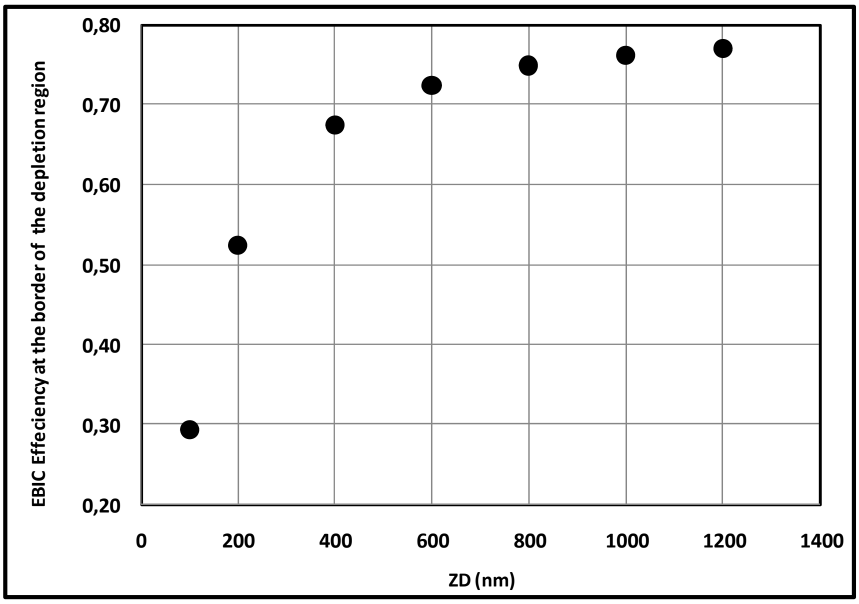


Figure 3 Variation of the EBIC collection efficiency profiles of a nano Schottky contact of radius r_c = 100 nm in a silicon sample at 5 keV in the case of an infinite surface recombination velocity ($v_s = \infty$) for different values of the depletion region radius z_D (see online version for colours)



We have also investigated the variation of the EBIC collection efficiency at the border of the depletion region versus the radius z_D. The results are reported on the Figure 4.

Figure 4 Variation of the EBIC collection efficiency at the border of the depletion region versus the radius z_D of a nano Schottky contact of radius r_c = 100 nm in a silicon sample at 5 keV in the case of an infinite surface recombination velocity ($v_s = \infty$)



This Figure 4 shows an increase followed by nearly a saturation of the efficiency when the depletion region increases. We can explain this result by the following: At the edge z_D of the depletion region, the generation volume is divided into two parts of different collection probabilities: a portion in the depletion region characterised by a probability collection equal to one and the other located outside characterised by a probability collection less than one. When the depletion region increases the internal part of the generation volume increases leading to an increase of collected carriers, thus an increase of the collection efficiency. As z_D increases further and becomes close to the depth of the generation volume, the fraction of carriers generated in the depletion region becomes constant, thus the saturation of the collected current.

4 Conclusions

We have used a Monte Carlo algorithm to compute the EBIC collection efficiency of a nano Schottky contact represented as disc of finite diameter. The depletion region that is induced in a semiconductor by a circular Schottky contact has a hemispherical form of radius z_D. The profile of the EBIC collection efficiency versus the distance to the centre of the nanocontact is simulated for different values of the radius z_D and two extreme values of the free surface recombination velocity ($v_s = 0$ and $v_s = \infty$) at 5 keV. The results show that the values of the efficiency obtained for $v_s = 0$ are greater than those obtained for $v_s = \infty$ and increase with the increase of the radius z_D. These results are reasonably predictable since the probability that carriers are collected increases with this parameter. The investigation shows also an increase followed by nearly a saturation of the EBIC efficiency at the border of the depletion region when this last increases.

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