C-V MEASUREMENT OF A DOPING PROFILE OF δ-DOPED GaAs AND ITS SPATIAL RESOLUTION — NUMERICAL STUDY *

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We have studied numerically the ability of C-V profiling method to describe precisely δ-doped concentration in the semiconductor. C-V doping profiles were modelled for a special input value of doping concentration using C-V curves calculated within a drift-diffusion approximation. The calculated free carrier concentrations for applied votages were used to simulate C-V behaviour and a capacitance doping concentration profile of the sample. The maximum apparent doping concentration extracted from the simulation process is slightly lower than the δ-doping concentration input. Certainly δ-peak in concentration could not be reproduced with an absolute fidelity. The width of the calculated concentration peak at its bottom is several semiconductor Debye lengths. The concentration peak is shifted very slightly to the bulk of the semiconductor. The shape of the calculated concentration profile was practically not influenced by the position of the layer in the depletion region.

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1 Introduction

In recent years the technology of a planar δ-doping of semiconductors has substantially improved. It makes possible to concentrate ionized doping atoms into a thin sheet layer and to increase the mobility of free carriers. The Dirac delta-function has been sometimes used to describe such impurity profile. From a fundamental point of view, δ-doped stuctures are very interesting because they enable to study the interaction between the electrons and charge impurities in the limit of very strong coupling. The studies are prevalently concentrated on n-type δ-doping. Experimentally it is a problem to obtain an accurate concentration profile for the structures with step change in doping concentration. Methods of measurement are secondary ion mass spectroscopy and C-V analysis. C-V technique originally developed to determine distribution profiles in heterojunction can also be applied to semiconductor structures with confined carriers [1]. The localization of the impurities should be done with an accuracy within the lattice constant of the host material [2]. Reverse bias applied to the Schottky structure causes a charge transfer from the confining well. The technique has been also used for studying periodically δ-doped semiconductors [3,4].

In this paper we try to analyse how precisely enables classical C-V profiling technique to determine the δ-doping concentration. Our approach is classical, we do not study in this paper electronic subband structure of the semiconductor which is sometimes argued to have an influence on C-V profile [5].

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2   Numerical method

The capacitance–voltage technique is a frequently used method for investigation of the carrier distibution in semiconductor structures. It was originally developed for homogeneously doped materials. According to the paper of Johnson and Panousis [6] the steps in the doping profile in semiconductors that occur in a distance smaller than the Debye length cannot be resolved satisfactorily. Profiles obtained from C-V measurement should be expected to provide a spatial resolution of the order of a Debye length. On the contrary, it has been found in [7] that the spatial resolution of the capacitance-voltage profiling depends on the spatial extent of the wave function and the Debye length limitation does not apply.

The analysis of capacitance as a function of bias voltage is conveniently done using depletion approximation where semiconductor is assumed to be composed of the two regions — the first which is totally depleted of free electrons and the second — quasineutral part of the semiconductor where charge neutrality holds. This concept assumes zero Debye length and sharp edge of the depletion layer. This assumption may lead to serious errors in concentration profiles calculated from C-V data for cases with large concentration gradients or even step concentration changes.

In conventional analysis of C-V data minority carriers are neglected throughout and it is assumed that in the depletion region free carrier concentration is zero and the rest of the semiconductor is electrically neutral. On the basis of these simplifications the following relationship is derived for the apparent carrier concentration and capacitance data

$$N(w) = -\frac{C^3}{q\varepsilon}(dC/dV)^{-1}, \tag{1}$$

where

$$w = e/C. \tag{2}$$

We have studied the influence of a planar δ-doping on C-V curves of Schottky diodes by simulations of C-V curves within a drift-diffusion approximation. It requires the solution of Poisson and the drift-diffusion equations

$$\Delta\varphi = -(q/\varepsilon_s)(p - n + N_d + N_a)$$
$$\frac{\nabla \cdot \mathbf{J}_n}{q} = U, \qquad \mathbf{J}_n = q(-\mu_n n \nabla\varphi + D_n \nabla n) \tag{3}$$
$$\frac{\nabla \cdot \mathbf{J}_p}{q} = -U, \quad \mathbf{J}_p = q(-\mu_p p \nabla\varphi - D_p \nabla p),$$

where φ is the electrostatic potential, q is the elementary charge, ε_s is the dielectric constant of semiconductor, n and p are the electron and hole densities, respectively, μ_n, μ_p, D_n, D_p and $\mathbf{J}_n$, $\mathbf{J}_p$ are respectively the mobilities, diffusion coefficients and the currents of electrons and holes, and U is the net recombination rate. The net recombination was considered to be zero. The Schottky boundary conditions were applied at the metal semiconductor interface, i. e., the quasi-Fermi levels were coincident at the interface with the Fermi level of the metal. Charge neutrality and thermodynamic equilibrium were assumed at the ohmic contact of the diode. The system of differential equations was discretized and solved by an iterative technique which used
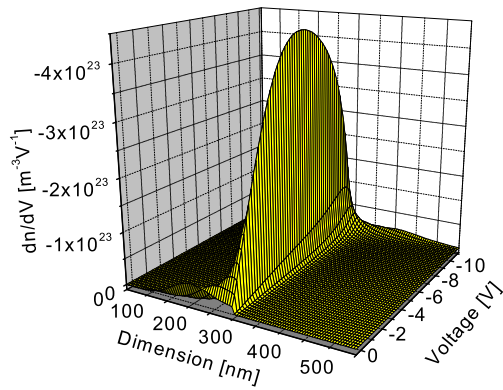
Fig. 1. Free carrier changes as a function of applied voltage and the distance from the Schottky contact on the semiconductor surface. The δ-doped layer is situated in the middle of 500 nm thick slab of GaAs.
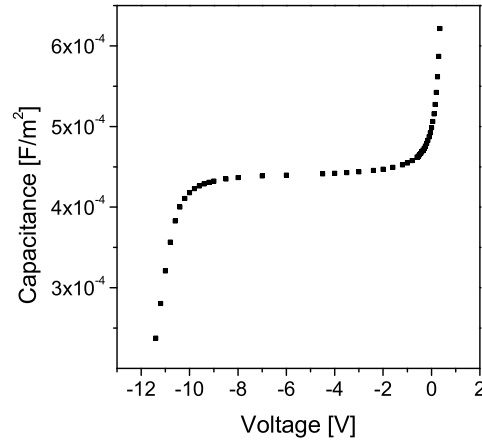
Fig. 2. C-V curve of the structure with the δ-doped layer is situated in the distance 250 nm from the Schottky contact.

Gummel's block iteration technique [8] and was developed by Mayergoyz [9] and Korman and Mayergoyz [10].

The δ-doped layer had sheet carrier concentration 3×10^{16} m^{-2} and was assumed to be 5 nm thick. The total thickness of the studied structure was 500 nm. The background doping concentration of GaAs was 1×10^{22} m^{-3}. Schottky barrier heigth of the structure 0.8 V was taken to calculations. The δ-doped layer was placed into two different depth in the semiconductor. First it was in the middle of the sample 250 nm under the surface and in the second case the distance from the surface was 125 nm. As a result of the calculation both majority and minority carrier concentrations in the structure were obtained. The calculated carrier concentrations were used to simulate C-V behaviour of the sample. Our simulations represent so called low-frequency C-V curves because there was no frequency limit for the free carriers to follow the changes of external bias.

3   Results and discussion

The charge response of single slices of the semiconductor to an external voltage was calculated and mapped. It is confirmed that as a reaction to the external voltage increment the free carrier concentration changes on a distance of several tens of nanometers and not only at the back edge of the space charge region [6]. Contribution of minority carriers to the device capacitance was found to be negligible throughout the whole bias range studied.

In Fig. 1 it is seen how the free carrier concentration responds to the changes of applied bias across the thickness of the semiconductor. The distance of the the δ-layer from the gate is 250 nm for this case. It is seen that for small forward and reverse voltages the electron concentration is changing in the depletion layer but already for these biases there is also a contribution from the δ-doped layer. For increasing reverse bias practically all electron concentration changes are situated to the δ-doped layer. The electron concentration peak is getting thinner and higher. Having
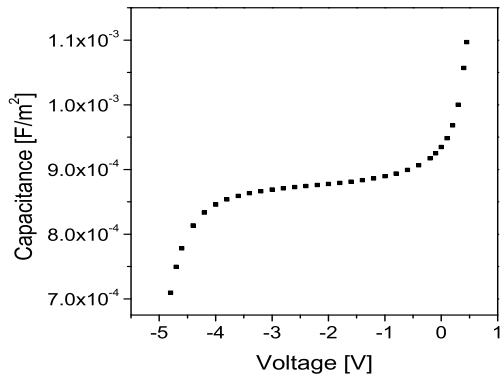
Fig. 3. C-V curve of the structure with the δ-doped layer is situated in the distance of 125 nm from the Schottky contact.
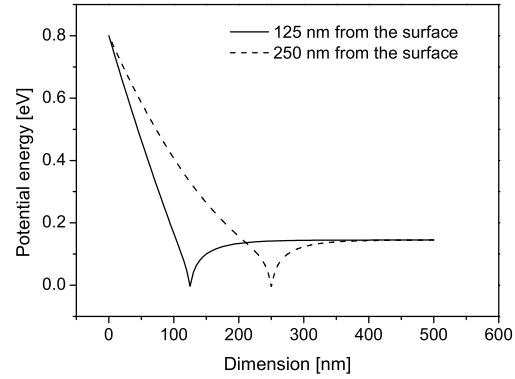
Fig. 4. Electrostatic potential energy for the two different positions of the δ-doped layer in the structure — 125 and 250 nm from the surface.

reached maximum it again enwidens but now towards the other edge of the semiconductor with simultaneous lowering. The whole process is relatively well symmetric around the middle of the structure.

In Figs. 2 and 3 calculated capacitances for the two structures with the δ-doped layer distance from the gate 250 and 125 nm, respectively, are shown. Capacitance of the structure has been calculated as a differential one, i.e., as a change of the charge in the structure with external bias. The difference in the charge between the two close voltages is caused practically by the change in the charge carried by electrons. A plateau occurs in curves for voltages at which the capacitance is determined by the changes of the charge in the δ-doped layer and the region near to the δ-doped layer. In Fig. 4 the potential for the two positions of the δ-doped layer is shown.

Calculated apparent doping concentrations for studied positions of δ-doped layer in the structure are presented in Figs. 5 and 6. Apparent doping concentrations are shown both in linear and logarithmic scale. In logarithmic scale one can see where and how precisely it is possible to detect the doping concentration step from the background concentration 10^{22} m^{-3}. Full line presents the assumed concentration profile – input into the calculations and dots are calculated apparent doping concentrations in the structure. The Debye length for GaAs with the used doping concentration is 42 nm. The maximum doping concentration in the δ-doped layer is well reproduced by the calculation for both δ-layer positions. The theoretical peak of the concentration is slightly shifted (1–2 nm) from the middle of the layer inside the semiconductor. This effect has been already mentioned by Liu and Lee [11] but its reason is not clear. The position of the δ-layer in the semiconductor has remarkable effect on the apparent concentration profile. The distance from the δ-layer in which the simulated value returns again to the background doping concentration is for our case approximately two Debye lengths. These results are comparable with the results of Johnson and Panousis[6]. For smaller distance of the δ-layer from the surface and small forward bias — the left tail of the left curve in Fig. 5 — the depletion approximation is not already valid and the value of doping concentration does not approach the background concentration. The minority carrier capacitance is not negligible in this region and calculated
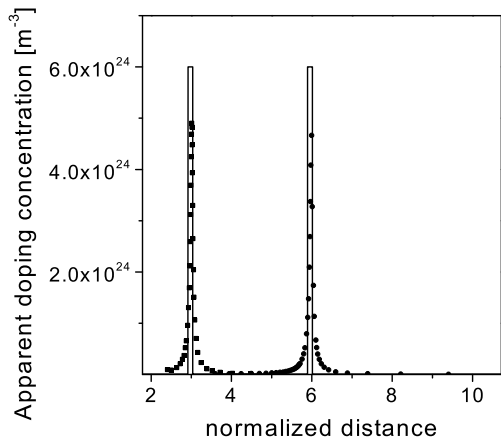
Fig. 5. Calculated doping concentration profiles for both δ-doped layer positions in linear scale, the distance is in Debye lengths.
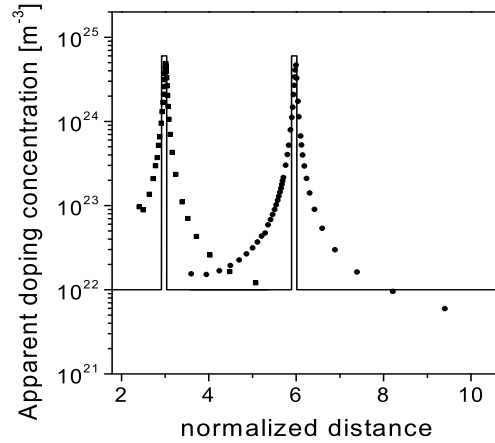
Fig. 6. Calculated doping concentration profiles for both δ-doped layer positions in logarithmic scale, the distance is in Debye lengths.

apparent free carrier concentration accoording to (1) and (2) does not reflect reality. Our results for δ-doped layer structure are comparable to the results of Ref. 6 where one-sided step and ramp profiles were studied.

4   Conclusions

In conclusion we have shown by numerical simulation of the differential capacitance profiling technique the possibilities of the C-V profiling technique applied to the δ-doped semiconductor. Primary obstacle limiting the resolution of the method for these structures is the fact, that the measurement of ionized doping concentration is mediated through the free carrier concentration whose distribution is coupled with dopant atoms distribution through Poisson equation. It is obvious that the free carrier distribution cannot follow step changes in concentration profile of dopant atoms and this effect limits the final resolution of the technique.

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