QUANTITATIVE PROFILING OF DOPANT CONCENTRATION IN SEMICONDUCTOR BY SECONDARY ELECTRON EMISSION

Filip MIKA, Doctoral Degree Programme (2)
Dept. of Microelectronics, FEEC, BUT
E-mail: xmikaf@feec.vutbr.cz

Supervised by Dr. Luděk FRANK

ABSTRACT

The dopant concentration in semiconductor is quantitatively determined by means of secondary electron emission. Determination is based on measurement of the secondary electron contrast in an electron optical image, observed between differently doped regions. Explanation of the contrast mechanism is proposed on the basis of experimental data collected in a low energy scanning electron microscope.

1 INTRODUCTION

Industry of semiconductor components needs fast diagnosis and quality control of the ever-diminishing feature size of modern semiconductor structures. The scanning electron microscope is a popular tool to use in this respect due to its wide range of magnification, the availability of a number of different signal modes, its speed of data acquisition and nondestructive nature of the technique in general, particularly at low voltage operations. The dopant concentration in the semiconductor can been determined in many different ways. In our case the determination is based on the measurement of the secondary electron contrast between differently doped regions in semiconductors.

2 CONTRAST MECHANISM

Secondary electron contrast of doped semiconductors was first attributed to the local electric fields above the surface, which are created by non-uniformities in the surface potential. These fields are called patch fields and appear between the N- and P-type regions at the semiconductor-vacuum interface [2]. The patch fields modify the vacuum level outside the sample. According to this model (see Fig. 1A), the P-type regions appear brighter than the N-type because of adequate differences in height of the potential barrier. For N-type regions the potential barrier is increased with respect to un-doped regions by some ΔE, thus preventing a larger portion of low energy SE that are generated in the bulk substrate from escaping the surface. For P-type regions this barrier is lowered, hence increasing the yield of

SE with respect to the N-type regions. The different SE yields result in a discernible contrast (levels of brightness) between differently doped regions when imaged in the SE mode.

Nevertheless, according to this model the contrast should entirely vanish, when the Fermi energy is pinned mid-gap because of high density of surface states (see Fig 1B). However, experiment showed [3] that when one part of a P/N structure was in-situ cleaned by ion beam (creating high density of surface states) and the rest leaved in as-inserted state, some residual contrast was still observed (see Fig. 2).

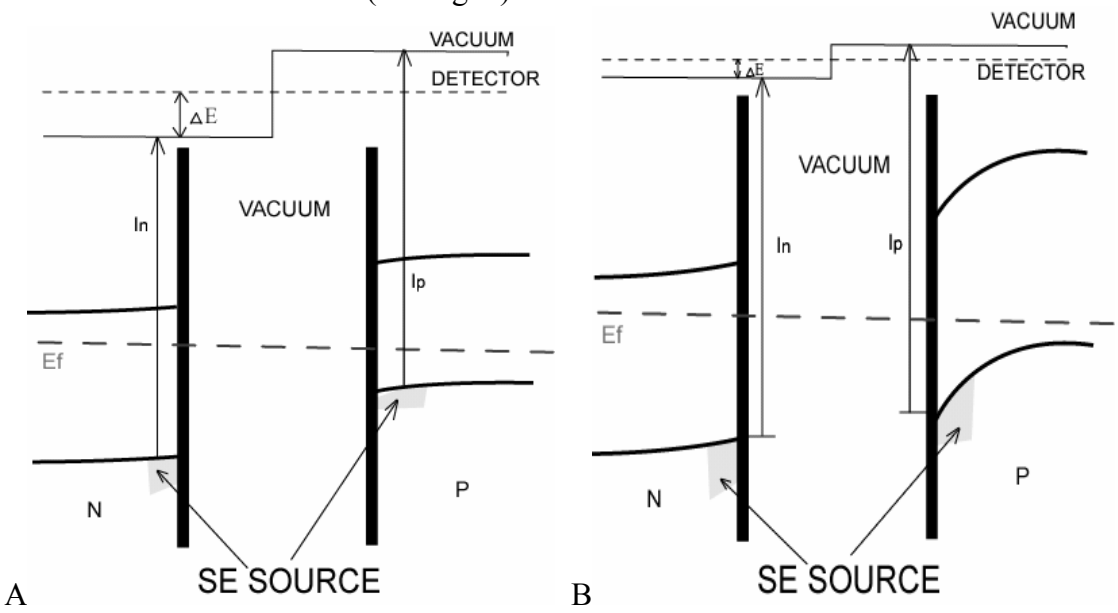

Fig. 1: *Schematic energy band structures of vacuum-to-semiconductor contacts: a) low density of surface states, b) high density of surface states and strong band bending.*

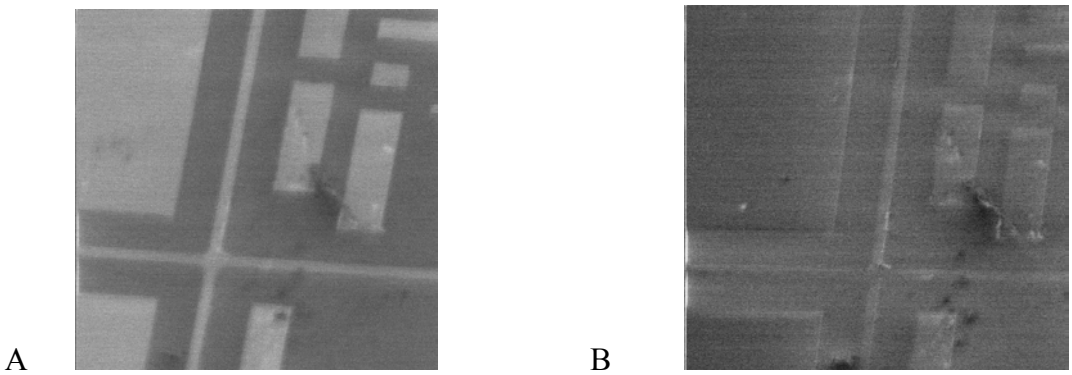

Fig. 2: *P-doped patterns on N-type Si: a) without surface states, b) with high density of surface states.*

In the new model, the SE contrast is explained to be due to a graphitic carbon film that may grow naturally on the semiconductor surface owing to cracking of adsorbed hydrocarbons under primary electron impact during SEM imaging. The carbon film could give rise to a metal-to-semiconductor contact structure of both rectifying (Schottky) and non-rectifying (ohmic) character, depending on the semiconductor type it is in contact with and on the relation between work functions of metal and semiconductor.

The carbon work function is higher than that of Si and when C is deposited on the N-type regions it should produce a Schottky type metal-to-semiconductor contact . Because the Fermi level of the semiconductor is initially higher than that in the metal, electrons from the semiconductor subsurface move into the metal and leave behind positive donor ions creating a space charge region, which is balanced by a much thinner layer of excess electrons in the metal. The electrostatic field is established by this double layer, which repels electrons moving from the semiconductor to the metal. This field also acts upon the incident beam induced hot electrons capable of being emitted as SE, but this concerns both P- and N-types to a similar extent. However, when in contact with the P-type Si, the C layer causes the bent valence band margin crossing the Fermi level so that the degenerated layer offers enhanced amount of electrons with lower bonding energy (see Fig. 3).

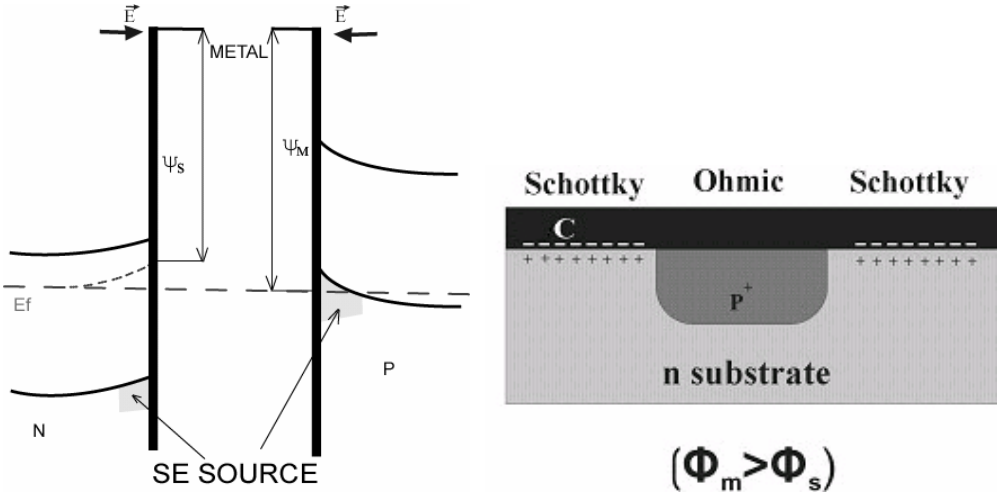

Fig. 3: *Metal-to-semiconductor contacts between metal of a work function ϕ_m higher than that of semiconductor ϕ_s, with both N- and P-type situation indicated.*

3 RELATION BETWEEN CONTRAST AND IMPACT ELECTRON ENERGY

As we mentioned above a contrast is observed between areas with reverse conductivity and is determined by the equation:

$$C_{P/N} = \frac{S_P - AF - S_N + AF}{S_N - AF} \tag{1}$$

where S_p and S_n are the signals from P or N areas. AF is a correction factor, which transforms S_p and S_n data to the absolute scale of the signal according to the background level BL(m) at which the picture was taken. For determination of AF we have to know the dependence of the "black level" for digital zero BL(0) on the gain G of the photomultiplier (see Tab. 1). This is measured for zero primary beam current.

$$AF = K\left[BL(0) - BL(m)\right] \tag{2}$$

$$K = \frac{255}{BL(0) - BL(255)} \tag{3}$$

GAIN G [%]	10	20	30	40	50	60	70	80	90
BL(0) [%]	64,8	64,8	64,8	64,9	64,9	65,1	65,1	65,2	65,7
BL(255) [%]	52,3	52,3	52,3	52,3	52,5	52,5	52,5	52,8	53

Tab. 1: *Relation between the black levels for the dark current, transformed to 0 and 255 digital units, on the gain G of photomultiplier.*

4 EXPERIMENTAL

The experiment was made with SEM type BS 343 with low energy electron adaptation. The microscope works in standard vacuum with pressure in the specimen chamber in the range 10^{-3} Pa. A silicon sample doped with boron atoms to a concentration of 1×10^{19} cm^{-3}, forming wells about 5 μm deep in phosphorus doped N-type <111> Si substrate, was used throughout this experiment. The sample was first ultrasonically cleaned and then dipped in 10:1 H_2O : HF for 5-10 min to remove any native oxide on the surface and to passivate it.

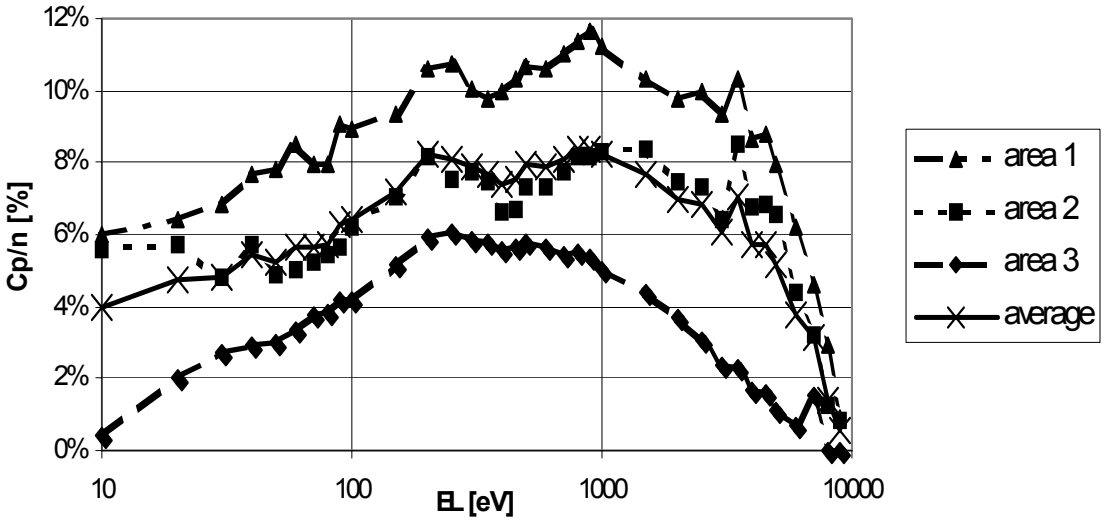

Fig. 4: *The energy dependence of the P / N contrast, calculated according to Eq. (1).*

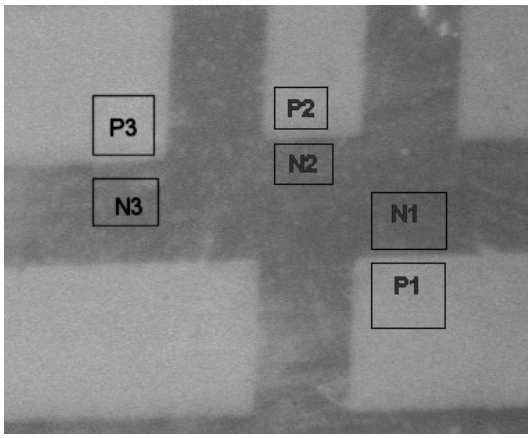

Fig. 5: *Definition of the P and N areas for the contrast measurement.*

In the experiment we observed a dependence of the measured contrast on the impact energy of electrons within an interval 10 – 9000 eV (Fig. 4). As we can see the contrast in low energy electron imaging reaches it's maximum at the impact energy around 1000 eV and falls to low values at margins of the interval measured. This result is in accordance with previously published data [1]. Important are great variations in the contrast magnitude between different places on the specimen. These can be ascribed to local variations in thickness and even composition of adsorbed and cracked carbonaceous layers.

5 CONCLUSION

The experiments demonstrated that specimen preparation, aiming at removal of the oxide layer, greatly influences magnification of the measured contrast. Also the thickness of the contamination graphitic layer, supposed to spontaneously grow on the surface, has strong impact on the contrast. These conclusions support the realization about the crucial role of the planar surface junctions and hence sub-surface instead of above-surface fields.

In the near future semiconductor structures with different dopant concentration, crystallographic orientation and different type of surface conductivity will be observed. The aim is to precise the model of contrast formation and to upgrade it to the quantitative level.

ACKNOWLEDGEMENTS

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