Scanning Capacitance Microscopy on Epitaxial Si Layers

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In this work, the physical processes leading to contrast in Scanning Capacitance microscopy (SCM) are investigated both experimentally and theoretically. Using a p-type silicon epitaxial staircase structure we show that a monotonic dependence of the SCM signal on the doping level is only obtained if the tip bias is adjusted in a way that the sample is either in accumulation or depletion. In the transition region, the SCM signal is non monotonic because depending on bias, any doping concentration can yield a maximum SCM signal size. We also show that this behavior is in excellent agreement with the conventional model of a metal-oxide-semiconductor junction.

1. Introduction

Scanning Capacitance Microscopy [1] (SCM), an extension of conventional Atomic Force Microscopy (AFM), is a promising tool for semiconductor device characterization. The main application of this method is two-dimensional carrier profiling for failure analysis or process control especially on cross-sectional samples. The current state of the art of this technique can be found in the review articles [2] – [4]. However, SCM is not an easy and straightforward to use technique. In detail, quantitatively reproducible measurements are a serious problem, since sample preparation has a dramatic influence on the results especially in cross-sectional measurements. According to the literature, best results are obtained on samples polished with silica slurry [5], [6], followed by a low temperature oxidation in an oven [7], [8]. Usually temperatures below 350 °C are used to avoid diffusion processes which would lead to a broadening of the investigated doping profiles. Alternatively, irradiation with UV light and simultaneous oxidation through *in-situ* generated ozone [9], or a combination of these two approaches [10], [11] is employed.

In addition to these technical problems, the physical processes leading to contrast in SCM images are not fully understood. Recently, a non-monotonic behavior of the SCM signal for large dynamic range samples was observed, and the influence of the applied DC bias [12] was studied qualitatively. Further an influence of light on the SCM signal [13] was found. Apart from this, the influence of adsorbed water on the sample surface on the resolution has been published [14], [15].

To obtain quantitative results, calibration samples such as epitaxial staircase structures [16], [17] are often used. However, simple calibration attempts immediately fail when the investigated structure size reaches the order of the depletion length in the semicon-

ductor, or the diameter of the AFM-tip. Thus, intensive simulations were carried out to study the limitations of the calibration curve method for determining doping profiles [18]. In general it turns out that quantitative 2D doping measurements on small structures are obviously impossible without inverse modeling [19] or detailed simulations using empirical databases [20] – [22].

2. Experimental

In this work, we investigate the physical processes leading to SCM contrast both experimentally and theoretically. Using conventional Metal-Oxide-Semiconductor (MOS) theory [23], [24] and epitaxial staircase structures we show that the maximum SCM signal strongly depends both on doping and the applied bias. The sample we used was a CVD-grown doping staircase prepared by AMS (*Austria Mikro Systeme International AG*) and consists of five nominally 400 nm thick p-type Si-layers having doping concentrations of 2.1×10^{15}, 2.0×10^{16} , 1.7×10^{17} 2.2×10^{18} and 9.1×10^{18} cm^{-3}, respectively. The highest concentration is located at the sample surface. The substrate is p-doped silicon with a concentration below 1×10^{15} cm^{-3}. The dopant concentrations were determined by a SIMS measurement the result of which is shown in Fig. 1. To avoid the usual problems related to sawing and polishing procedures in sample preparation for cross-sectional AFM/SCM measurements the samples were cleaved and subsequently oxidized in UV-light [9] – [11]. For the back contact, sputtered aluminum was employed. The capacitance measurements were performed using the Dimension-3100 system with integrated SCM sensor (Digital Instruments, USA). The probes implemented for the investigations were conducting diamond tips (Nanonsensors, Germany) which turned out to be superior to metal coated tips due to their high resistance against abrasion. Space charge effects in such tips can be neglected as long as the dopant concentration in the tip (10^{20} at/cm^3) is much higher than in the sample.

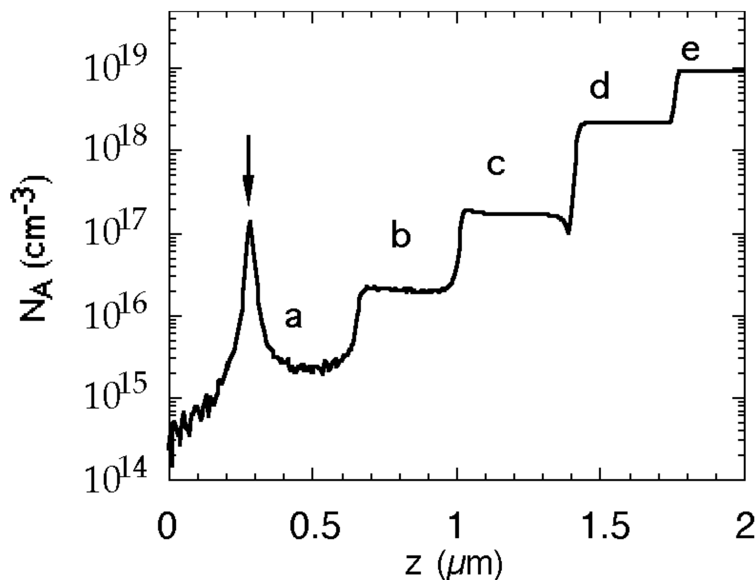

Fig. 1: Doping profile of our epitaxial staircase structure determined by SIMS. The sample surface is on the right hand side. The peak at z = 0.25 μm is an unintentional artifact of the epitaxial process.

Before we discuss our SCM data, we have to introduce the following important convention concerning the bias polarity: In analogy to textbooks on conventional MOS theory [23], [24], the bias in this work is always plotted in a way as if it would be applied to the AFM tip. In reality this is not the case, since in the DI-3100 SCM the bias is applied to the substrate for technical reasons. Finally, it needs to be mentioned that the SCM only measures the derivative of the capacitance, dC/dV, and not the capacitance itself.

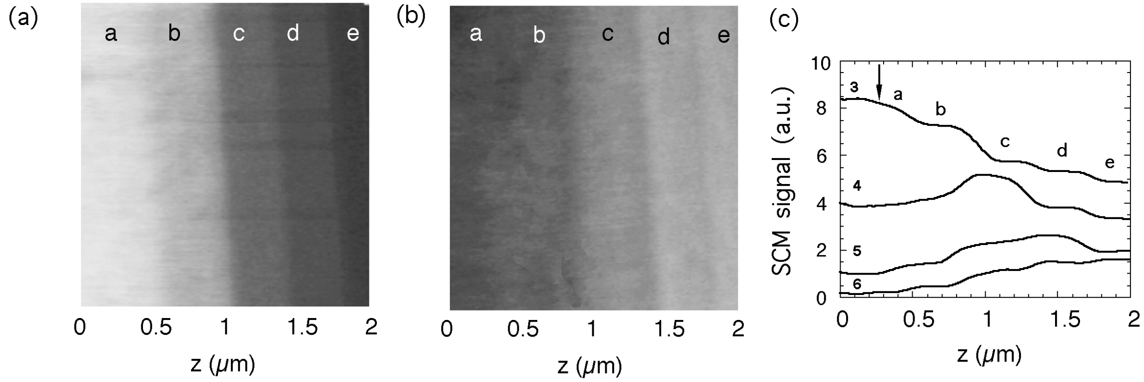

Fig. 2: (a) SCM image of our sample taken at a bias of –1.9 V. Image (b) was recorded at +0.8 V. The regions (a), (b), (c), (d) and (e) have doping concentrations $2.1x10^{15}$, $2.0x10^{16}$, $1.7x10^{17}$, $2.2\ x10^{18}$ and $9.1x10^{18}$ cm^{-3} , respectively.
(c): Sections through SCM images taken at a bias of +0.8 V, 0 V, –0.5 V and –1.9 V (curves 3-6). The numbering of the curves corresponds to the numbering in Figure 3.

Figure 2 shows cross sectional SCM images of our sample measured at two different bias values. The sample surface is on the right hand side. Figure 2(a) was measured at a tip bias of –1.9 V and Fig. 2(b) at V = +0.8 V. As one can see, the contrast between these two images is reversed. Figure 2(c) shows sections through SCM images perpendicular to the growth direction and measured at four different bias values. Two features are evident: First, the 400 nm wide differently doped layers are clearly visible as well defined steps in the SCM signal (see curve (3) e.g.). As a consequence we conclude that geometry effects of the tip can be neglected otherwise the steps would be washed out. This washout, however is nicely seen for the doping spike at the substrate interface, the position of which is marked by an arrow both in curve (3) and the SIMS data (Fig. 1). As the spike is much narrower than the steps and already in the same order as the radius of the tip (100 nm), only a small dip is observed in curve (3) instead of the expected well pronounced minimum.

As second feature in Fig. 2(c), the contrast dependence as a function of bias, can be seen in detail. At –1.9 V (curve 3), the SCM signal decreases with increasing doping. At +0.8 V (curve 6), however, this behavior is reversed and the SCM signal increases monotonically with increasing doping concentration For bias values of –0.5 V and 0 V the behavior is non monotonic, and the maximum of the SCM signal is observed in regions (c) and (d), respectively.

Although the bias induced contrast reversal was already reported in the literature [12], a detailed study of this behavior was not carried out up to now. To explain the origin of this behavior, we consider an ideal p-Si/SiO_2/Al junction as model system and use con-

ventional MOS theory. Figure 3 (a) shows the corresponding C(V) and dC/dV curves, where the y-axis of the dC/dV was flipped for better comparison with the experimental data. For the calculation an acceptor concentration of $N_A = 1x10^{16}$ cm^{-3}, an oxide thickness of 3 nm (a typical thickness for SCM), and no traps or surface charges were assumed. Other parameters could also be chosen, but have no qualitative influence on the obtained result. At low bias, the sample is in accumulation, which means that the capacitance is high, because it is mainly determined by the oxide thickness. The dC/dV peak marks flatband conditions, and above 0.9V, the area under the gate becomes depleted. To explain the non-monotonic behavior of the SCM contrast, we simply calculate dC/dV as a function of the acceptor concentration N_A at various constant bias values both in the accumulation and the depletion regime. As our considerations apply for n- and p-type samples and the sign of the SCM output depends on the phase adjustment of the built in lock-in amplifier, we consider the absolute value of dC/dV for convenience. The result of this calculation is shown in Fig. 3 (b) where the curve numbers correspond to the bias values marked by arrows in Fig. 3 (a). In accumulation (curves 1 – 3), the SCM signal always decreases exponentially with increasing doping. Further, the signal increases when the bias approaches the region of the maximum in the dC/dV curve. Under depletion conditions (curves 4 – 6), the situation is complex. For bias values close to the dC/dV maximum, the SCM signal shows a clear maximum for doping concentrations around $N_A = 1x10^{16}$ cm^{-3} (curve 4). This maximum shifts to higher concentrations when the sample goes deeper into depletion (curves 5, 6). In addition, the signal size decreases. At a bias of 1.1 V (curve 6) a situation is achieved where the maximum is close to $N_A = 1x10^{19}$ cm^{-3}. Above that bias, the SCM signal becomes very small but monotonically increases in the whole regime between $N_A = 1x10^{15}$ cm^{-3} and $N_A = 1x10^{19}$ cm^{-3}.

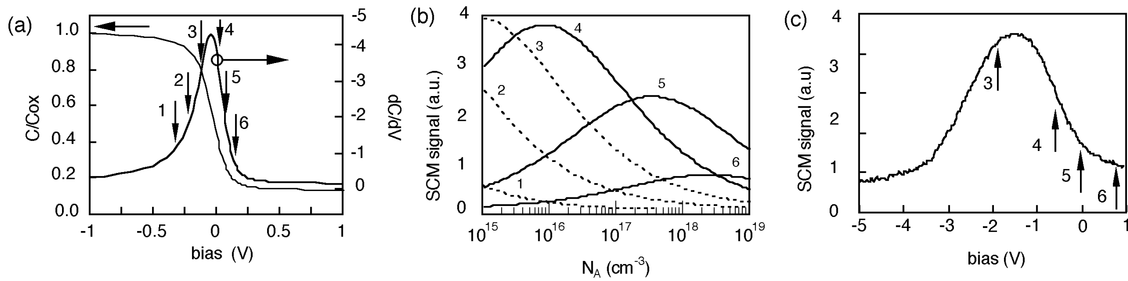

Fig. 3: (a) calculated C(V) and dC/dV curves of an ideal p-Si/SiO_2/Al junction. The y-axis of the dC/dV plot was flipped for better comparison with the experimental data. (b): SCM signal plotted as a function of N_A for different constant bias values as labeled in Figure 3(a). (c) typical dC/dV curve measured with our SCM. The arrows labeled with (3-6) indicate those bias values at which curves (3 – 6) in Fig. 2 (c) were taken.

If we now compare the measured SCM signal in the differently doped areas with the calculated behavior in Fig. 3(b), one can see that the experimental curves (3 – 6) in Fig. 2(c) clearly correspond to the calculated curves (3 – 6) of Fig. 3(b). Thus, it becomes clear why the SCM signal decreases with increasing doping concentration in accumulation and vice versa in depletion. In the transition regime, any doping concentration can yield highest contrast depending on bias.

To verify this further, we also measured dC/dV curves using our SCM. Figure 3(c) shows typical data. Again, the absolute value of the SCM signal is plotted for convenience. Compared to the calculated dC/dV curve of an ideal p-Si/SiO_2/Al junction (see Fig. 3(a)), the position of the peak is shifted to negative bias, which is due to surface charges and the use of a diamond tip having a different surface barrier height than aluminum. In addition, the peak is much broader, which is mainly due to the tip geometry [25]. The arrows (3 – 6) indicate the bias positions where curves (3 – 6) of Fig. 2(c) were measured. As one can see, bias positions (4 – 6) are located on the right hand side of the dC/dV peak, which is the bias regime where the sample moves from accumulation into depletion. At bias position (3) the sample is still completely in the accumulation regime. This good agreement nicely shows that the experimental situation indeed qualitatively corresponds to our idealized model system.

For practical SCM applications some conclusions can now be drawn: To obtain unambiguous results, the bias position of the maximum in dC/dV has to be known. Then, the bias should be chosen in a way that the sample is either in accumulation or depletion. According to our experience, the accumulation region yields more reproducible results, probably due to the fact that deep depletion is difficult to achieve because of the influence of the laser beam necessary for the AFM feedback control. Note that the dC/dV maximum shifts with doping concentration so that one has to stay in a save distance from the dC/dV maximum in order to avoid to enter the transition regime between accumulation and depletion by accident. Finally, care should be taken on samples where both p-type and n-type regions exist. If the bias is adjusted in a way that the sample is in accumulation in the p-type regions, it will be in depletion in the n-type regions. As a consequence, the contrast is reversed in the n-type region and also the signal will be small. Moreover, measurements at zero bias, as often found in the literature on pn-junction imaging, might yield unpredictable contrast behavior.

3. Conclusion

In summary, we have investigated the bias dependent SCM contrast on a p-type silicon doping staircase. We have found, that a monotonic behavior of the SCM signal as a function of doping is only obtained if the sample is either in sufficient accumulation or depletion. In the transition region, the behavior is non-monotonic, and the maximum SCM signal size depends both on doping concentration and applied bias. The observed behavior is in good agreement with conventional MOS theory and theoretically applies for p- and n-type samples.

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References

[1] D.D.Bugg, P.J.King, J.Phys. E21, 147 (1988)

[2] V.V. Zavyalov, J.S. McMurray, C.C. Williams, Rev. Sci. Instr. 7, 158 (1999)

[3] P. De Wolf, R. Stephenson, T. Trenkler, T. Clarysse, T. Hantschel, W. Vandervorst, J.Vac. Sci. Technol. B18, 361 (2000)

[4] R.Stephenson, P.DeWolf, T.Trenkler, T.Hantschel, T.Clarysse, P.Jansen, W.Vandervorst, Vac. Sci. Technol. B18, 555 (2000)

[5] F. Giannazzo, F. Priolo, V. Raineri, V. Privitera, Appl. Phys. Lett. 76, 2565 (2000)

[6] J.S. McMurray, J. Kim, C.C. Williams, J. Vac. Sci. Technol. B15, 1011 (1997)

[7] G.H. Buh, H.J. Chung, C.K. Kim, J.H. Yi, I.T. Yoon, Y. Kuk, Appl. Phys. Lett. 77, 106 (2000)

[8] J. Schmidt, D.H. Paoport, G. Behme, H.-J. Fröhlich, J. Appl. Phys. 86, 7094 (1999)

[9] J.J. Kopanski, J.F. Marchiando, B.G. Rennex, J. Vac. Sci. Technol. B18, 409 (2000)

[10] V. A. Ukraintsev, F.R. Potts, R.M. Wallace, L.K. Magel, H. Edwards, M.-C. Chang, AIP Conf. Proc. 449, 736-740 (1998)

[11] V.V. Zavyalov, J.S. McMurray, S.D. Stirling, C.C. Williams, H. Smith, J. Vac. Sci. Technol. B18, 549 (2000)

[12] R.Stephenson, A.Verhulst, P.DeWolf, M.Caymax, W.Vandervorst, Vac. Sci. Technol. B18, 405 (2000)

[13] C.C.Williams J.Slinkman, W.P.Hough, K.Wickramasinghe, Vac. Sci. Technol. A8, 895 (1990)

[14] N.Nakagir, T.Yamamoto, H.Sugimura, Y.Suzuki, Vac. Sci. Technol. B14, 887 (1996)

[15] S.Lany, Surf. Interface Anal. 27, 348 (1999)

[16] T.Clarysse, M.Caymax, P.DeWolf, T.Trenkler, W.Vandervorst, J.S.McMurray, J.Kim, C.C.Williams, J.G.Clark, G.Neubauer, Vac. Sci. Technol. B16, 394 (1998)

[17] J.S.McMurray, J.Kim, C.C.Williams, Vac. Sci. Technol. B15, 1011, (1997)

[18] J.F.Marchiando, J.J.Kopanski, J.Albers, J. Vac. Sci. Technol. B18, 414 (2000)

[19] Y.Huang, C.C.Williams, J.Slinkman, Appl. Phys. Lett. 66, 344 (1995)

[20] J.F.Marchiando, J.J.Kopanski, J.R.Lowney, J. Vac. Sci. Technol. B16, 463 (1998)

[21] L.Ciampolini, M.Ciappa, P.Malberti, W.Fichtner, V.Ranieri, (preprint, submitted)

[22] J.J.Kopanski, J.F.Marchiando, J.R.Lowney, J. Vac. Sci. Technol. B14, 242 (1996)

[23] S.M. Sze, Physics of Semiconductor Devices, John Wiley & Sons Ltd, New York, 1981

[24] E.H. Nicollian, J.R. Brews, MOS (metal oxide semiconductor) physics and technology, John Wiley & Sons Ltd, New York 1982

[25] L.Ciampolini, private communication