The Diffusion Current in Shallow Co-silicided Junctions

A. Poyai[1], E. Simoen[2] and C. Claeys[2,3]
[1]Thai Microelectronics Center (TMEC), National Electronics and Computer Technology Center,
National Science and Technology Development Agency,
51/4 Moo 1, Wang-Takien District, Amphur Muang, Chachoengsao 24000, Thailand
[2]IMEC, Kapeldreef 75, B-3001 Leuven, Belgium
[3]also at: KU Leuven, ESAT-INSYS, Leuven, Belgium

ABSTRACT – This paper demonstrates that the diffusion current in shallow cobalt-silicided n^+p junction diodes strongly increases with increasing deposited cobalt (Co) thickness (t_{Co}). The increase is related to the enhanced minority carrier recombination current in the neutral emitter region which becomes smaller for higher t_{Co}. This is supported by the recombination lifetimes in the p-type substrate, derived from cross-sectional Microwave Absorption measurements, showing no dependence on the processing conditions. From the measured diffusion current density, one can derive the Gummel number of the emitter, which can be considered as a measure for the effective recombination properties in the highly doped region.

KEY WORDS - diffusion current, junction diode, Gummel number

บทคัดย่อ – ในบทความนี้จะแสดงให้เห็นว่ากระแสที่เกิดจากการแพร่ในไดโอดแบบรอยต่อ n^+-p ที่มีโคบอลต์ซิลิไซด์ จะเพิ่มขึ้นอย่างมากเมื่อเพิ่มความหนาของโคบอลต์ที่เคลือบ ซึ่งการเพิ่มขึ้นสัมพันธ์กับการเพิ่มขึ้นของกระแสเนื่องจากการรวมตัวของพาหะส่วนน้อยในบริเวณเป็นกลางของอิมิตเตอร์ โดยบริเวณนี้จะมีขนาดเล็กลงเมื่อความหนาของโคบอลต์มีค่ามากขึ้น สมมติฐานนี้ได้รับการยืนยันจากค่าเวลาการรวมตัวของพาหะส่วนน้อยในฐานรองชนิดพี ซึ่งทำการวัดโดยการดูดกลืนคลื่นไมโครเวฟของภาคตัดขวาง (cross-sectional Microwave Absorption measurements) พบว่าค่าที่วัดได้ไม่ขึ้นอยู่กับเงื่อนไขของกระบวนการผลิต จากค่าความหนาแน่นของกระแสแพร่ที่วัดได้จะสามารถคำนวณค่าตัวเลขกัมเมลของชั้นอิมิตเตอร์ ซึ่งสามารถพิจารณาได้เหมือนกับการวัดคุณสมบัติของการรวมตัวของพาหะส่วนน้อยในบริเวณที่มีการเจือสารสูงๆ

คำสำคัญ – กระแสแพร่, ไดโอดแบบรอยต่อ, ตัวเลขกัมเมล

1. Introduction

Downscaling CMOS technologies not only requires a reduction of the lateral device dimensions, but also of the source/drain junction depths. To achieve this goal, one has to reduce the thermal budget. However, this does not guarantee the complete removal of the ion implantation induced damage, which can enhance the diode leakage current when present in the depletion region. Another problem is related to the silicidation of the junction, which consumes part of the highly doped emitter region. It is well-known from the past that when the silicide interface comes too close to the junction, a drastic increase of the diode leakage current is observed [1-2]. It is therefore not a surprise that the formation of low-leakage shallow junctions is an interesting topic [3-5].

The focus in this paper is on the diffusion current density J_{diff} in shallow cobalt-silicided junctions. For deep p-n junctions, Shockley-Read-Hall theory predicts that the saturation value is given by [6]:

$$J_{diff} = \frac{qn_i^2}{N_A}\sqrt{\frac{D_n}{\tau_n}} + \frac{qn_i^2}{N_D}\sqrt{\frac{D_P}{\tau_p}} \qquad (1)$$

with n_i the intrinsic carrier concentration; q the elementary charge; N_A, N_D the doping density in the p- and n-side of the junction, respectively; D_n the diffusion coefficient of electrons (p-side) and D_p for holes (n-side) and τ_p (τ_n) the corresponding minority carrier lifetime. For asymmetric junctions, i.e. $N_A << N_D$, the recombination current in the neutral part of the highly doped n$^+$ region (emitter) can be neglected compared with the diffusion current of the p-base (substrate). In such a case, the diffusion current density can be utilised to derive the minority carrier lifetime in the silicon substrate [7-8]. However, when the base (or substrate) is more highly doped, both terms in Eq. (1) need to be considered. In that case, it is possible to derive also the minority carrier lifetime in the emitter region, from the experimental diffusion current [6,9].

For shallow n$^+$p junctions, Eq. (1) can be approximated in first instance by [10]:

$$J_{diff} = \frac{qn_i^2}{N_A}\sqrt{\frac{D_n}{\tau_n}} + \frac{qn_i^2}{N_D}\frac{D_P}{d_{ne}} \qquad (2)$$

which neglects surface recombination and assumes homogeneous material parameters in the emitter region. Here, d_{ne} is the thickness of the neutral emitter region, extending from the silicide interface to the edge of the depletion region on the n$^+$ side. As can be seen from Eq. (2), for sufficiently small d_{ne}, the recombination current in the highly doped n$^+$ region may no longer be negligible compared with the substrate contribution. This can, for example, occur when during silicidation a large part of the highly doped region is consumed. This effect is studied here for a series of Co silicided n$^+$p junctions, corresponding to different thickness of deposited Co (t_{Co}).

2. Experiments

Co-silicided n$^+$p junctions were processed on 150 mm p-type Cz wafers, with a typical doping density of 6x10^{14} cm^{-3}, as derived from high-frequency Capacitance-Voltage (C-V) measurements. The junctions have been formed by an arsenic implantation at 70 keV, using a dose of 3x10^{15} cm^{-2}. Dopant activation was achieved by an 1100 ^{o}C rapid thermal anneal (RTA) for 10 sec. The junctions have been silicided, using a different thickness of the sputtered Co layer t_{Co}, as indicated in Table I. Figure 1 shows cross-sectional Transmission Electron Microscopy (TEM) micrograph for the Co thickness of 30 nm. The non-silicided reference wafer received a standard Al metallization, corresponding to an original junction depth (d_j) of about 0.15 µm. The arsenic profile in the n$^+$ region has been determined by SIMS measurements. The remaining emitter thickness of Table I is calculated assuming a resulting silicide thickness of:

$$t_e = d_j - 3.73t_{Co} \quad \text{(in nm)} \qquad (3)$$

Current-Voltage (I-V) and C-V measurements have been performed at 25 ^{o}C on five large area (A=10 mm^2) and five large perimeter diodes (P=8.04 cm) per wafer. Combining either the forward or the reverse I-V characteristics of the area and perimeter diodes, one can separate first the geometrical leakage current components [11]. Next, the saturation value of the diffusion current density can be extracted either from the forward I-V, as demonstrated previously [8], or from the reverse volume current density, using a recently developed procedure, which is also valid for shallow junctions, suffering from field-enhanced generation effects [12]. Combining the C-V data of the area and perimeter diode yields the doping profile $N_A(W)$ in the substrate and the depletion width (W), which are used in the current separation [8,11-12].

Table I. Processing parameters and ideality factor (m) of the exponential part of the forward diode characteristics.

deposited Co thickness (t_{Co}) (nm)	emitter thickness (t_e) (nm)	ideality factor (m)
0 (no)	150	1.10
12	106	1.14
20	77	1.12
30	41	1.03
20 + 10 nm Ti	77	1.06

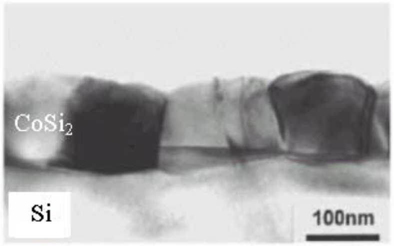

Figure 1. Cross-sectional Transmission Electron Microscopy (TEM) micrograph for the Co thickness of 30 nm.

The recombination lifetime in the bulk has also been measured directly using time-resolved microwave (MW) photoconductivity measurements at Vilnius University. The principle of the technique and the data analysis is described elsewhere [13].

3. Results

The silicidation has a very strong impact on the I-V characteristics as can be derived from Fig. 2. The current in both forward and reverse polarization increases strongly with increasing Co thickness, in agreement with previous studies [1-3]. Nevertheless, the ideality factor (Table I) of the diodes are good, ranging between 1.03 and 1.14, in agreement with other reports [3]. This indicates that in the ideal forward region, the current is dominated by the diffusion mechanism. No important generation-recombination (GR) or tunneling component is observed there.

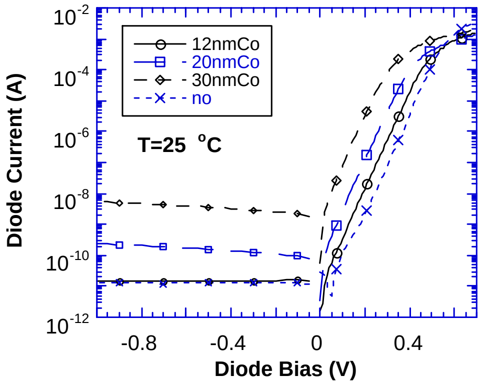

Figure 2. I-V characteristic at 25 ^{O}C for a set of 10 mm^2 diodes, corresponding to different deposited Co thickness.

Figure 3 represents the saturation value of the diffusion current density extracted from the forward and the reverse I-V. Note first of all that within 20 % the same value for J_{diff} is derived from both methods, demonstrating the consistency of the extraction [8,12]. Secondly, J_{diff} shows a strong, close to exponential variation with t_{Co} (or with t_e, taking account of Eq. (3)). The observed increase is much stronger than the reciprocal one predicted by Eq. (2), suggesting that this equation is rather qualitative than quantitative.

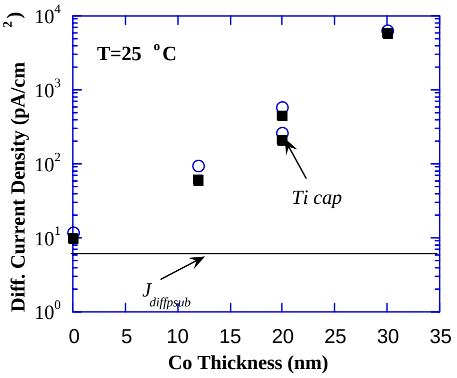

Figure 3. Diffusion current density derived from the forward (open circles) and the reverse (closed squares) I-V, for the diode set of Table I.

It has been suggested on a number of occasions that silicidation injects point defects in the silicon and therefore introduces generation/recombination centres in the diode depletion region and deeper in the substrate, which increase the generation and the diffusion current [1-2]. In order to test this hypothesis, it was decided to perform MW measurements, the results of which are summarized in Fig. 4. From the effective recombination lifetime derived from the transient microwave signal, following a laser pulse excitation, both the bulk lifetime and the surface recombination velocity can be exctracted [13]. Here, the light excitation was performed in a cross section of the sample, enabling the assessment of the lifetime parameters close to the junction, which was not removed for the analysis. It is evident from Fig. 4 that the silicidation has a marginal impact on the bulk recombination lifetime, which is around 30 µs.

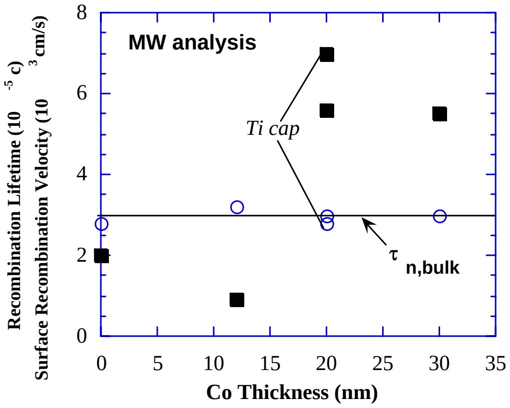

Figure 4. MW bulk recombination lifetime (circles) and surface recombination velocities (squares) as a function of the Co thickness.

Having ruled out a possible change in the bulk recombination properties, we are led to the conclusion that the change in J_{diff} is related to the emitter region. However, as shown above, Eq. (2) is not an adequate description to account for the recombination in the neutral emitter. A better approximation is given by [3]:

$$J_{diff,n} = \frac{qn_i^2}{G} \tag{4}$$

with G the Gummel number defined by:

$$G = \int_0^{d_{ne}} \frac{N_D(x)}{D_{heff}(x)} \exp\left(\frac{\Delta E_G}{kT}\right) dx \tag{5}$$

whereby $N_D(x)$ is the free carrier profile in the n^+ region, D_{heff} the effective hole diffusivity and ΔE_G the corresponding band-gap narrowing which is also position dependent. Equation (4), on the one hand, takes account of the high-doping effects on the band-gap (n_i) and on the diffusivity, and, on the other hand, accounts for the profile in the doping density. Literature models have been used for ΔE_G and D_{heff}, in order to calculate G [14].

Experimental G-values have been derived from the saturation diffusion current density as follows. First, for all diodes the diffusion current density corresponding to a lifetime of 30 µs and a D_n =35 cm^2/s has been calculated and subtracted from the measured value. The result should correspond to the emitter contribution, given by Eq. (4). Figure 5 compares the experimental with the calculated Gummel number. From the figure, a good qualitative agreement is observed, whereby both curves seem to be shifted over about 20 nm. More detailed calculations reveal that the Gummel number is very sensitive to the actual dopant profile in the emitter region close to the junction. However, it is clear that for shallow junctions below 100 nm, an increase in the diffusion current density by roughly one decade occurs for an emitter consumption of 30 nm. This is in line with other estimates which can be found in literature [5].

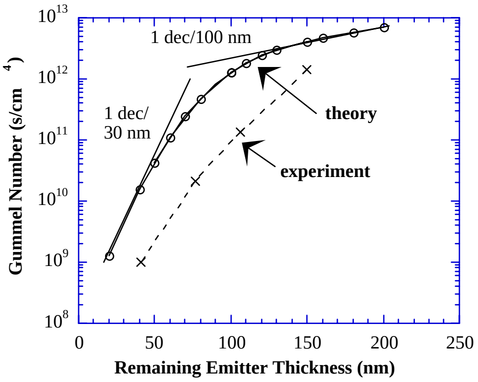

Figure 5. Calculated and experimental Gummel number for different starting junction depths versus the remaining emitter thickness.

From the calculations follows that the steep increase of the diffusion current density is explained by the fact that for shallow junctions, the arsenic profile is governed by the exponential tail of the profile, while for deeper junctions with respect to the silicide interface, the flat part of the dopant profile is not consumed and corresponds to an increase of 1 decade in diffusion current for every 100 nm consumed. This implies that the diffusion current may impose a limitation to the further down-scaling of p-n junctions, when it exceeds a certain threshold. It is furthermore a sensitive function of the activated dopant profile [5,10]. Of course, for very shallow junctions below about 50 nm, other transport mechanisms like thermionic emission become dominant and should be considered [10].

4. Conclusion

The impact of the diffusion current due to minority carrier transport in the remaining n^+ emitter has been clarified. It is believed that it imposes a fundamental lower limit for the diode leakage, which should be considered for the development and modeling of (ultra) shallow junctions.

5. Acknowledgment

K. Maex, B. Mohadjeri and A. Lauwers from IMEC are acknowledged for very stimulating discussions and for providing the SIMS profile. The authors would like to thank E. Gaubas from Institute of Material Research and Applied Sciences, Vilnius University in Lithuania for time-resolved microwave (MW) photoconductivity measurements. The authors also thank A. Czerwinski from Institute of Electron Technology, Poland for very stimulating discussions. A. Poyai acknowledges the Thai government scholarship supported through the National Science and Technology Development Agency (NSTDA) of Thailand during his stay at IMEC.

References

[1] J. Amano, K. Nauka, M.P. Scott, J.E. Turner and R. Tsai, "Junction leakage in titanium self-aligned silicide devices", Appl. Phys. Lett, vol. 49, pp. 737-739 (1986).

[2] R. Liu, D.S. Williams and W.T. Lynch, "A study of the leakage mechanisms of silicided n^+p junctions", J. Appl. Phys., vol. 63, pp. 1990-1999 (1988).

[3] F. La Via and E. Rimini, "Electrical characterisation of ultra-shallow junctions formed by diffusion from a $CoSi_2$ layer", IEEE Trans. Electron Devices, vol. ED-44, pp. 526-534 (1997).

[4] C.-P. Chao, K.E. Violette, S. Unnikrishnan, M. Nandakumar, R.L. Wise, J.A. Kittl, Q.-Z. Hong and I.-C. Chen, "Low resistance Ti or Co salicided raised source/drain transistors for sub-0.13 µm CMOS technologies", in IEDM Tech. Dig., pp. 103-106 (1997).

[5] M.I. Current, E. Ishida, L.A. Larson and E.C. Jones, "Challenges of doping ultra-shallow transistor junctions for giga-scale devices", in Proc. of the Eighth Int. Symposium on Silicon Materials Science and Technology, Eds H.R. Huff, H. Tsuya and U. Gösele, The Electrochem. Soc. Proc. Vol. 98-1, The Electrochem. Soc. (Pennington, NJ), pp. 1196-1212 (1998).

[6] A. Neugroschel, F.A. Lindholm and C.-T. Sah, "A method for determining the emitter and base lifetimes in p-n junction diodes", IEEE Trans. Electron Devices, vol. ED-24, pp. 662-671 (1977).

[7] H. Aharoni, T. Ohmi, M.M. Oka, A. Nakada and Y. Tamai, "Analysis of n^+p junctions with varying substrate doping concentrations made under ultraclean processing technology", J. Appl. Phys., vol. 81, pp. 1270-1288 (1997).

[8] E. Simoen, C. Claeys, A. Czerwinski and J. Katcki, "Accurate extraction of the diffusion current in silicon p-n junction diodes", Appl. Phys. Lett., vol. 72, pp. 1054-1056 (1998).

[9] D.J. Roulston, N.D. Arora and S.G. Chamberlain, "Modeling and measurement of minority-carrier lifetime versus doping in diffused layers of n^+-p silicon diodes", IEEE Trans. Electron Devices, vol. ED-29, pp. 284-291 (1982).

[10] E.C. Jones and N.W. Cheung, "Modeling of leakage mechanisms in sub-50 nm p^+-n junctions", J. Vac. Sci. Technol. B, vol. 14, pp. 236-241 (1996).

[11] A. Czerwinski, E. Simoen, C. Claeys, K. Klima, D. Tomaszewski, J. Gibki and J. Katcki, "Optimised analysis of electrical silicon substrate properties", J. Electrochem. Soc., vol. 145, pp. 2107-2112 (1998).

[12] A. Poyai, E. Simoen, and C. Claeys "Impact of a high electric field on the extraction of the generation lifetime from the reverse generation current component of shallow n^+-p-well diodes", IEEE Trans. Electron Devices, vol. 48, pp. 2445-2446 (2001).

[13] E. Gaubas and J. Vanhellemont, "A simple technique for the separation of bulk and surface recombination parameters in silicon", J. Appl. Phys. vol. 80, pp. 6293-6297 (1996).

[14] J. Del Alamo and R.M. Swanson, "Measurement of steady-state minority-carrier transport parameters in heavily doped n-type silicon", IEEE Trans. Electron Devices, vol. ED-34, pp. 1580-1589 (1987).

Amporn Poyai was born in Pathum-thani, Thailand. He received the B.S. ('91) degree in physics from Silpakorn University, M.Eng. ('94) in electrical engineering from King Mongkut's Institute of Technology Ladkrabang (KMITL), both in Thailand. He obtained M.E. ('98) and Ph.D. ('02) in electrical engineering from Katholieke Universiteit Leuven (KU Leuven), Belgium. His doctoral research was in the field of device physics and defect engineering. In these fields, he has authored and co-authored over 60 Journal and Conference papers. In 1994, he joined NECTEC (Thailand), where he has been involved in the nation microelectronics project. From 1997 to 2002, he had got scholarship from Thai government supported through the National Science and Technology Development Agency (NSTDA) of Thailand to join IMEC (Belgium) for his master and doctoral research. Since 2002, he is a researcher of Thai Microelectronic Center (TMEC).

Eddy Simoen obtained his Masters ('80) and Doctoral Degree ('85) in Engineering from the University of Gent (Belgium). His doctoral thesis was devoted to the study of trap levels in high-purity germanium by deep-level transient spectroscopy. In 1986, he joined IMEC to work in the field of low temperature electronics. His current interests cover the field of device physics and defect engineering in general, with particular emphasis on the study of low-frequency noise, low-temperature behavior and of radiation defects in semiconductor components and materials. He is currently involved in a EU funded HRM Network called ENDEASD and devoted to defect engineering in irradiated and ion implanted silicon materials. In these fields, he has (co-) authored over 550 Journal and Conference papers and in addition 4 book chapters and a monograph on Radiation Effects in Advanced Semiconductor Devices and Materials (Springer, 2002). He was also co-editor of two International Conference Proceedings and was a lecturer at the International Noise School held at IMEC in 1993 and at the ENDEASD Workshop in Santorini (Greece; april 1999) and Stockholm (Sweden, June 2000).

Cor Claeys was born in Antwerp, Belgium. He received the electrical engineering degree in 1974 and the Ph.D. degree in 1979, both from the Katholieke Universiteit Leuven (KU Leuven), Belgium. His doctoral research was in the field of process-induced defect characterization for VLSI technologies. From 1974 to 1984 he was, respectively, Research Assistant and Staff Member of the ESAT Laboratory of the KU Leuven and is, since 1990, Professor. In 1984, he joined IMEC, Leuven, as Head of the Silicon Processing Group. Since 1992, he has also been responsible for technology business development. His main interests are in general silicon technology for ULSI, device physics including low-temperature operation, low frequency noise phenomena and radiation effects, and defect engineering and material characterization. He co-edited a book on “Low Temperature Electronics”, wrote a book on “Radiation Effects in Advanced Semiconductor Materials and Devices” and has authored and co-authored six book chapters and more than 400 technical papers and conference contributions related to the above fields. Dr. Claeys is a member of the Electrochemical Society, SEMI, and the European Material Research Society. He is an associate editor for the Journal of the Electrochemical Society. He was the founder of the IEEE Electron Devices Benelux Chapter and is presently elected AdCom member of the Electron Devices Society. In 1999 he has been elected as Academician and Professor of the International Information Academy.