Microelectronic Engineering 86 (2009) 1599–1602

Contents lists available at ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee

Inhomogeneous Ni/Ge Schottky barriers due to variation in Fermi-level pinning

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ARTICLE INFO

Article history:
Received 6 March 2009
Received in revised form 10 March 2009
Accepted 10 March 2009
Available online 20 March 2009

Keywords:
Electrodeposition
Schottky barriers

ABSTRACT

To achieve high performance Ge nMOSFETs it is necessary to reduce the metal/semiconductor Schottky barrier heights at the source and drain. Ni/Ge and NiGe/Ge Schottky barriers are fabricated by electrodeposition using *n*-type Ge substrates. Current (I)–voltage (V) and capacitance (C)–voltage (V) and low temperature I–V measurements are presented. A high-quality Schottky barrier with extremely low reverse leakage current is revealed. The results are shown to fit an inhomogeneous barrier model for thermionic emission over a Schottky barrier. A mean value of 0.57 eV and a standard deviation of 52 meV is obtained for the Schottky barrier height at room temperature. A likely explanation for the distribution of the Schottky barrier height is the spatial variation of the metal induced gap states at the Ge surface due to a variation in interfacial oxide thickness, which de-pins the Fermi level.

1. Introduction

To achieve high performance Ge nMOSFETs it is necessary to reduce the Schottky barrier height to the metal or germanide source and drain as much as possible. This reduction of barrier height is hampered by the extreme degree of Fermi-level pinning that takes place at the metal–Ge interface with the Schottky pinning parameter being virtually zero [1]. It has been recently shown that this pinning can be partly prevented by inserting a thin oxide layer at the interface between the metal and the semiconductor [2,3]. Discussion of the barrier height in Si and Ge metal–semiconductor contacts has usually been made assuming spatial uniformity of the barrier height. However, it has be shown clearly by both other and us [4,5] that in case of Si any physical interpretation of the discrepancy of the barrier height as derived from current (I)–voltage (V) and capacitance (C)–voltage (V) characteristics as well as the non-Arrhenius behaviour of the temperature dependence can only be explained by assuming a spatially inhomogeneous barrier height. In this paper, we show that the same analysis is valid in Ni–Ge and by extension NiGe–Ge Schottky barrier contacts and we discuss the results in the light of the potential mechanisms responsible for Fermi-level pinning, in particular metal induced gap states (MIGS) [6,7].

2. Experimental procedure

For the fabrication of Ni/Ge SBs, Antimony-doped Ge (100) wafers were taken as the starting wafers. Square patterns of sizes from 20 to 400 μm square were transferred to the photoresist-coated substrates by conventional lithography. The back ohmic contacts were defined by Au–Sb evaporation and annealing the samples in an H_2/N_2 inert atmosphere. Subsequently, a 20:1 buffered HF dip for 30 s, followed by DI water wash, was performed to remove any native oxides. For electrodeposition, a Ni sulphate bath and an Autolab AUT72032 potentiostat three-electrode system with a Pt counter electrode and a saturated calomel reference electrode (SCE) were used. In order to determine an optimum deposition potential for Ni deposition on Ge, a cyclic voltamemogram was initially obtained for various Ge substrates. A typical cyclic voltamemogram of Ni electrodeposition on Ge having a resistivity of 2–2.4 Ω-cm is presented in Fig. 1. Here, Ni nucleation started at −0.9 V (against the SCE). Between −0.9 to −1.5 V, the cathodic current was dominated by Ni deposition (between the arrows in Fig. 1). Therefore, the deposition potential could be within this region. For Ni electrodeposition on the various photoresist patterned Ge substrates, the deposition potential was chosen between −1.10 and −1.15 V. The film thickness was monitored during electrodeposition by observing the charge accumulated at the cathode.

SBs with Ni layer thicknesses from 70 nm to 200 nm were fabricated, but no variation of the SB parameters with thickness was observed. I–V and C–V characteristic measurements were performed using a Hewlett Packard 4155 C semiconductor parameter analyzer and a Hewlett Packard 4280 A, 1 MHz, C Meter/(C–V) plotter, respectively. The low temperature measurements were performed using a Bio-Rad DL 4960 cryostat temperature controller that enables a temperature variation from 1.5 K to room tempera-

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doi:10.1016/j.mee.2009.03.097

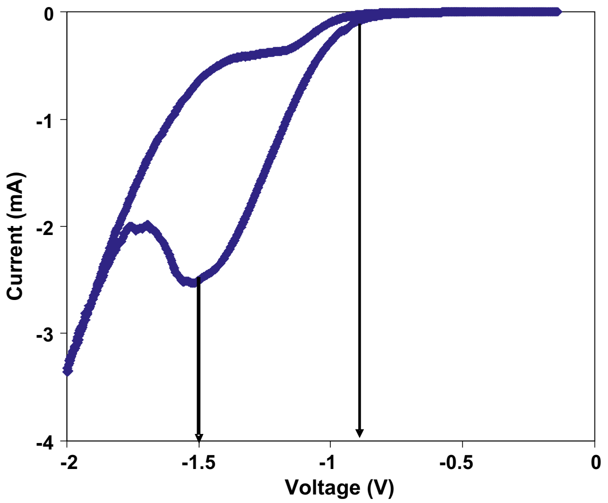

Fig. 1. Cyclic voltamemogram of Ni electrodeposition on Ge with resistivity of 2–2.4 Ω-cm.

ture. Germanidation of the Ni films was performed for 20 min in the anneal chamber at temperatures ranging from 300 °C to 500 °C. X-ray diffraction and Scanning Electron Microscopy (SEM) measurements where performed using a Siemens D5000 X-ray Diffractometer and a LEO 1455VP SEM. More details, on the Germanidation process including SEM images and X-ray graphs, and metal sheet resistance can be found in our recent paper on Ge Schottky barrier MOSFETs [8].

3. Results and discussion

In Fig. 2, we show the current density (*J*) vs. *V* characteristics of the Schottky barriers prepared on lowly doped nGe (2–2.4 Ω-cm) and highly doped n^+Ge(0.005–0.02 Ω-cm) for Ni/Ge and for highly doped n^+Ge after the Germanidation process leading to NiGe/Ge Schottky barriers. The contact areas of the SBs on the lowly doped and highly doped Ge are 400 μm and 20 μm square, respectively. Using the Richardson constant value for free electrons ($A^* = 50\ \mathrm{A\ cm^{-2}\ K^{-2}}$ [9,10]), electron SB heights ϕ_n in the range of 0.52–0.55 eV are obtained for all three devices. The ideality factors (η) and the series resistances (R_S) are also extracted. These are summarised in Table 1.

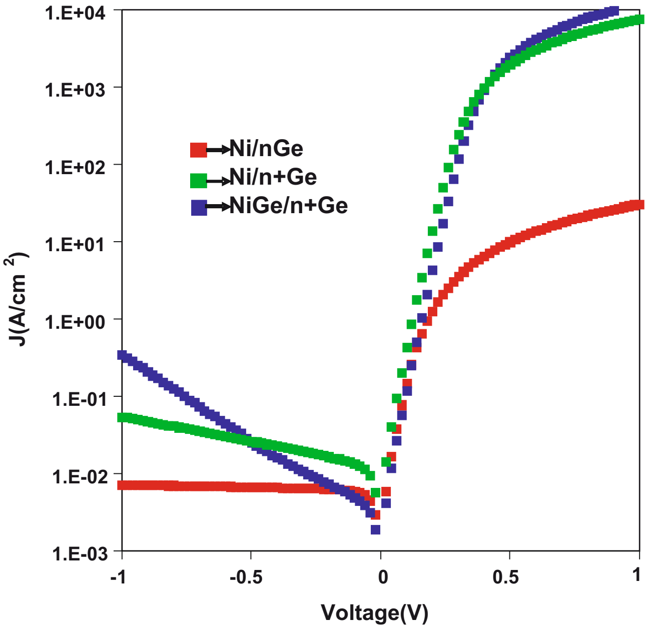

Fig. 2. *J*–*V* characteristics of electrodeposited Ni–Ge and NiGe–Ge Schottky barriers for different Ge doping concentrations clearly demonstrating the effect of Fermi-level pinning on the barrier height.

The reverse leakage matches the saturation current density and has a low field dependence. Breakdown of the diodes was not observed up to −3-V bias, indicating that edge effects are suppressed as explained in our previous work [11]. This is a clear indication that the Fermi-level pinning is as strong in electrodeposited Ge Schottky barriers as it is in evaporated barriers suggesting that intrinsic effects are responsible for the Fermi-level pinning. We continued with a detailed characterisation of the electrodeposited NiGe Schottky barriers. Lowly doped nGe substrates are used in the following analysis to eliminate tunneling effects and allow for a description of the Schottky barriers by thermionic emission (TE) theory only.

C–*V* measurements of Schottky barriers on plain Ge were performed for an A^*-independent measurement of the Schottky barrier height. An inverse square capacitance vs. voltage characteristic is shown in Fig. 3. As expected, a straight line is observed, and from its intercept on the voltage axis the Schottky barrier height is calculated to be 0.569 eV [12]. Furthermore, from the slope of this characteristic, the Ge doping concentration can be extrapolated. A value of $8.7 \times 10^{-14}\ \mathrm{cm^{-3}}$ is obtained, corresponding to a resistivity of 1.84 Ω-cm, which is very close to the specification of the Ge substrate used (2–2.4 Ω-cm).

Low temperature *I*–*V* measurements were performed for the same devices. The range was from 50 K to 300 K, with steps of 10 K. The forward bias characteristics are shown in Fig. 4. For clar-

Table 1
Extracted ϕ_n of the Ni/nGe, Ni/n^+Ge and NiGe/n^+Ge Schottky diodes.

Device	ϕ_n (eV)	η	R_S (Ω)
Ni/nGe	0.53	1.18	12.40
Ni/n^+Ge	0.52	1.1	21.32
NiGe/n^+Ge	0.55	1.08	10.85

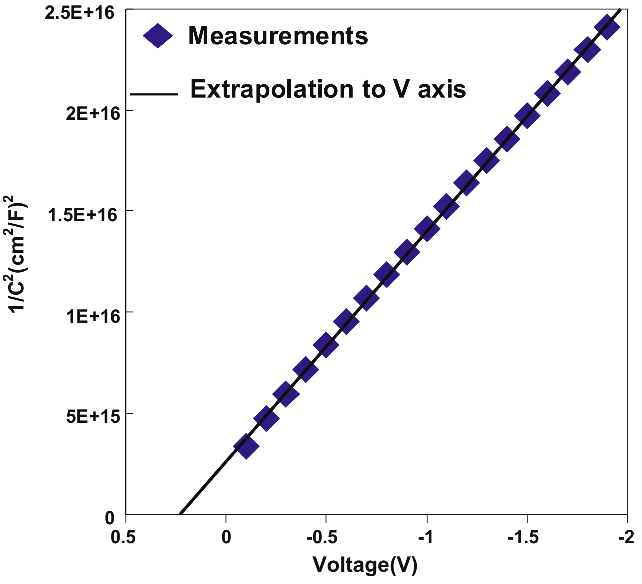

Fig. 3. C^{-2}–*V* curve of an electrodeposited Ni/Ge contact. For the measurements a 1 MHz signal with 30 mV rms was used. From this curve a SB height of 0.569 eV is extrapolated.

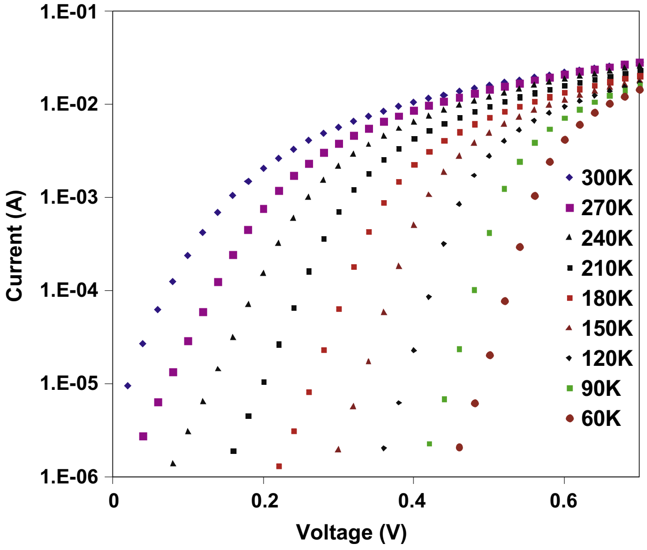

Fig. 4. Low temperature, forward bias *I–V* characteristics of an electrodeposited Ni–Ge SB with a contact area of 400 μm square.

ity, *I–V* curves of only 9 different temperatures are plotted in this diagram.

As expected from the thermionic emission theory, the saturation current (I_S) is reduced drastically with temperature. The reverse leakage current is also reduced following I_S (not shown in Fig. 4). Below 120 K, the reverse leakage is lower than 100 pA, which is the lowest current limit of the measurement setup that has been used.

The saturation current density was extrapolated from the *I–V* measurements for different temperatures by fitting the TE model in the low forward bias region in the current range of 1×10^{-4}–1×10^{-5} A, and the data were plotted in an activation energy diagram as shown in Fig. 5. A temperature independent Schottky barrier height would result in a straight line on the activation energy diagram. A fit with $\phi_n = 0.53$ eV is shown as a solid line in Fig. 5. This line fits only the high temperature experimental results. For lower temperatures, a deviation from a straight line is observed, indicating a temperature dependent Schottky barrier height.

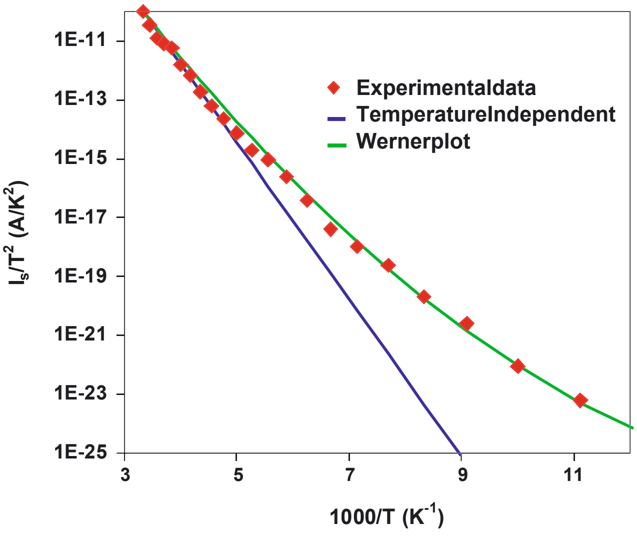

Fig. 5. Activation energy diagram (Arrhenius plot) of the same electrodeposited Ni/Ge contact as in Fig. 4. The measurements are fit using a temperature-independent SB height thermionic emission model (when $\phi_n = 0.53$ eV) and the model of Werner and Guttler [15] (when $\phi_n = 0.57$ eV and $\sigma_s = 52$ meV).

Several models have been proposed to explain the low temperature behaviour of Schottky barriers [13]. In order to model the temperature dependence of Schottky barrier heights, the so-called T_0 effect is often used [14]. However, it lacks a direct physical explanation [5]. A model that physically justifies the temperature dependence of Schottky barriers is that proposed by Werner and Guttler [15]. This model assumes a spatial distributions of the barrier height as described by a Gaussian function. The barrier height influences capacitance and dc current measurements differently. The capacitance stems from the displacement current, which depends on the mean electric field at the metal/semiconductor interface. Short-wavelength potential fluctuations at the metal/semiconductor interface are screened out at the edge of the space–charge region. Consequently, capacitance measurements reflect the mean value of the barrier height. On the other hand, the current across the interface depends exponentially on the barrier height and thus sensitively on the detailed barrier distribution at the interface. Any spatial variation in the barriers causes the current to flow preferentially through the barrier minima. A quantitative expression for the effective barrier height is given by the following equations:

$$J(V) = A^{*}T^{2}e^{-\frac{q\phi_n}{kT}}\left(e^{\frac{qV}{kT}} - 1\right) \qquad (1)$$

$$\phi_n = \overline{\phi_n} - \frac{q\sigma_s^2}{2kT} \qquad (2)$$

with $\overline{\phi_n}$ and σ_s being the mean value and the standard deviation of the spatial Schottky barrier height distribution, respectively.

As discussed, if the spatial distribution is on a length scale less than the space charge width, then $\overline{\phi_n}$ should match the Schottky barrier height value obtained by *C–V* measurements.

In order to fit our experimental results with this model, we use the Schottky barrier height value from *C–V* measurements, leaving the standard deviation as the only fit parameter. Again, a value of 50 A cm^{-2} K^{-2} for the Richardson constant is used. The resulting fit, using a standard deviation of 52 mV, is shown in Fig. 5. An excellent fit is obtained throughout the range of measurements. The value of the standard deviation of the barrier height is in good agreement with ballistic electron emission microscopy values on Au–Si [16]. The ideality factor which in most other models is just a fitting factor follows logically from this interpretation as well as outlined in Ref. [4,5]. These result hence indicates that the inhomogeneous Schottky barrier model is an accurate description for Ni/Ge Schottky barriers and that its assumption is probably basically correct.

The physical origin of the inhomogeneity of the Schottky barriers is open to interpretation. It can be argued that the polycrystalline nature of Ni at the Schottky barrier interface results in a variation in metal work function. However, the strong Fermi-level pinning strongly reduces the importance of the metal work function and the X-ray diffraction measurements only show the evidence of Ni(1 1 1) peak, this explanation is hence not satisfactory. If one assumes that metal-induced gap states (MIGS) at the semiconductor surface determine the barrier height, the inhomogeneity of the Schottky barriers must be due to the spatial variation of the MIGS. This variation might be due to the presence of a very thin oxide layer between the semiconductor and the metal. As shown in Ref. [3] a 0.6 nm thin GeO$_x$ layer between Al and nGe reduces the barrier height by 40 meV. Although we did not grow any oxide on purpose, it is likely that some GeO$_x$ would indeed have formed on the Ge surface before metal electrodeposition. A local variation (non-Gaussian) in this oxide thickness of the order of 0.5 nm would hence be consistent with the experimental data. It also suggests that for Fermi-level de-pinning a non-uniform oxide layer might actually be more beneficial than a uniform layer.

4. Conclusions

Electrodeposited Ni–Ge and NiGe–Ge Schottky barriers were characterised by *I–V*, *C–V* and low temperature *I–V* measurements. The temperature dependence of the *I–V* characteristics can be quantitatively fitted by taking into account a model for inhomogeneous Schottky barriers proposed by Werner and Guttler. A likely explanation for the spatial variation of the Schottky barrier height is the spatial variation of the metal induced gap states at the Ge surface due to a variation in interfacial oxide thickness.

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