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Comparative study of current–voltage characteristics of Ni and Ni(Pt)-alloy silicided $p^+/n$ diodes

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A comparative study of the $I$–$V$ characteristics of $p^+/n$ diodes silicided with a pure Ni and Ni(Pt) alloy has been performed. Higher saturation currents as well as abnormal reverse $I$–$V$ characteristics were observed for some of the diodes which were silicided with pure Ni at 700 °C while good $I$–$V$ characteristics were observed for other diodes. Our results show that the forward current in the diodes with good $I$–$V$ characteristics is dominated by electron diffusion in the $p^+$ region. For diodes with higher saturation currents, it has been concluded that both forward and reverse currents in these diodes are dominated by the current following through Schottky contacts that are formed due to inadvertent penetration of NiSi spikes through the $p^+$ region into $n$ region. The formation of Schottky contact was not observed in diodes silicided with a Ni(Pt) alloy, providing a clear evidence of enhanced thermal stability of Pt containing NiSi. © 2001 American Institute of Physics. [DOI: 10.1063/1.1374496]

NiSi is potentially an attractive silicidate material due to its low resistivity, less consumption of Si, and ability to maintain low resistivity even for linewidth down to 0.1 μm. While the thermal stability of the NiSi is the major concern for its application to deep submicron devices, it has been recently demonstrated that the addition of a small amount of foreign elements (e.g., 5% Pt) can significantly enhance the thermal stability of NiSi without increasing its resistivity. In this work, we have measured, analyzed, and compared the $I$–$V$ characteristics of Ni and Ni(Pt)-alloy silicided $p^+/n$ diodes. The results of this work reveal that, for pure Ni silicidation, an rapid thermal processing (RTP) silicidation at 700 °C or above may induce the formation of Schottky contacts in the $p^+/n$ junctions, resulting in higher saturation currents ($I_S$) and abnormal reverse $I$–$V$ characteristics. The results also show that the formation of Schottky contact can be avoided if a small amount of Pt (5 at. %) is added into Ni, providing a clear evidence of enhancement of the thermal stability of NiSi by the addition of Pt.

$p^+/n$ diodes were fabricated by 40 keV BF$_2$ implantation at $2 \times 10^{15}$ cm$^{-2}$ into n well in a boron doped p-type (100) silicon substrate with resistivity of 6–9 Ω cm and subsequent dopant activation annealing at 925 °C for 20 s. Pure Ni and Ni(Pt)-alloy (with 5% Pt) films, 250 Å thick, were deposited at room temperature after a dilute HF dip. The wafers were then subjected to a RTP annealing at 600 and 700 °C for 60 s in N$_2$ ambient for silicidation. Unreacted Ni was selectively etched off using H$_2$O$_2$+H$_2$SO$_4$ solution. The diodes were square shaped with an area of $1 \times 10^{-4}$ cm$^2$ each and a dopant concentration of about $2.6 \times 10^{17}$ cm$^{-3}$ in the $n$ region.

Figures 1(a)–1(d) show typical $I$–$V$ curves measured on $p^+/n$ diodes silicided with Ni or Ni(Pt) at 600 and 700 °C. The ideality factors and saturation currents are extracted from the forward $I$–$V$ curves in Figs. 1(a)–1(d) and shown in Fig. 2. As shown in these figures, good $I$–$V$ characteristics are observable for the majority of measured diodes except some of the diodes which were silicided with pure Ni at 700 °C. The ideality factors and saturation currents of the diodes with good $I$–$V$ characteristics are in the range of 1.01–1.08 and $2 \times 10^{-15}$–$9 \times 10^{-15}$ A, respectively. For the diodes with poor $I$–$V$ characteristics, the corresponding ranges are 1.11–1.13 and $5 \times 10^{-14}$–$3 \times 10^{-13}$ A. In addition to higher saturation currents, these diodes also exhibit abnormal reverse $I$–$V$ characteristics, i.e., drastically increased leakage current with increasing reverse bias.

It is well known that ideality factor is close to 1 when the forward current is dominated by diffusion current and becomes close to 2 in the presence of dominant recombination current. For the diodes with good $I$–$V$ characteristics, it is therefore believed that the forward current is dominated by the diffusion current. Assuming that no Schottky contacts are formed in these diodes, the saturation currents can be expressed as

$$I_S = A q D_p p_n / L_p + A q D_n n_p / W_{p+},$$

where $A$ is the diode junction area, $q$ is the electron charge, $D_{p,n}$ are hole/electron diffusion coefficients, $p_n$ and $n_p$ are equilibrium hole/electron concentrations in $n$/$p^+$ regions, $L_p$ is the hole diffusion length given by $(D_p \tau_p)^{1/2}$ with $\tau_p$ as the hole lifetime in $n$ region, and $W_{p+}$ is the width of $p^+$ neutral region. Using Eq. (1), the $L_p$ and $W_{p+}$ values are calculated assuming either hole or electron diffusion being dominant diffusion current. In the case of hole diffusion in $n$ region

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being the dominant diffusion current, we obtain $L_p \approx 1 \times 10^{-5}$ cm for a typical $I_S$ value of $5 \times 10^{-15}$ A, setting $\tau_p$ around $2.5 \times 10^{-11}$ s. This is an extremely low value for minority carrier lifetimes in Si, considering that normal minority carrier lifetime in device quality Si is in the range of a few microseconds to a few hundreds microseconds.

On the other hand, in the case of electron diffusion being the dominant diffusion current, we obtain a value of a few hundred angstroms for $W_p$, which is close to the thickness ($\approx 700$ Å) of the $p^+$ region. Therefore, it seems that the forward diffusion current in these diodes is dominated by electron diffusion in the $p^+$ neutral region.

For the diodes with higher saturation currents, it is tempting to attribute the observed higher saturation current and slightly higher ideality factor to the possible presence of an appreciable recombination current. However, this possibility is ruled out due to following two reasons. First, though slightly higher, the ideality factors $\approx 1.12–1.13$ of these diodes are still close to 2, but much lower than 2. Second, the ideality factor remains constant for forward bias up to the point where the series resistance effect becomes significant. For a diode with an appreciable recombination current, its forward $I-V$ curve normally features two distinguishable ideality factors, a value considerably larger than 1 in the lower voltage region and a value close to 1 in the higher voltage region. Therefore, the observation of a constant ideality factor suggests that recombination currents are not the dominant current sources under forward bias in these diodes.

The observed behavior of the forward current in the diodes with poor $I-V$ characteristics is analyzed in this paper from the viewpoint of Schottky contact being formed by inadvertent penetration of NiSi through the $p^+$ region into the $n$ region. This is based on the analyses of the Arrhenius plots for the saturation and leakage currents (Fig. 3). As shown in Fig. 3, the measured activation energies associated with the saturation current and reverse leakage current $I_R$ at 20.5 V are 0.62 and 0.58 eV, respectively. Assuming that these values are effective barrier heights of a Schottky barrier under different biases (i.e., 0 and 20.5 V), one obtains a value of 0.67–0.64 eV for the ideal barrier height $\phi_{BN}$, taking into account the lowering of the barrier height by the image force. The $\phi_{BN}$ value obtained (0.67–0.64 eV) is much smaller than Si band gap (1.12 eV), but very close to the barrier height of NiSi/n-Si (0.65 eV). This good agreement seems to provide a clear evidence that Schottky contacts are formed in the diodes with poor $I-V$ characteristics, and the forward currents in these diodes are dominated by the currents flowing through the Schottky contact areas. The effective Schottky
contact areas extracted using the measured saturation currents and the effective barrier height (0.62 eV) under zero bias are found to be less than 0.001% of the junction area of $1 \times 10^{-4}$ cm$^2$ (i.e., 0.066 $\mu m^2$ for the diode with the highest saturation current). In Fig. 3, one can also see that the saturation current activation energies (0.95–1.11 eV) of the diodes with good $I$–$V$ characteristics, obtained from $I_S/T^2$ vs 1000/$T$ curves, are close to the Si band gap (1.12 eV). This result further confirms our previous conclusion that the electron diffusion current dominates forward currents in these diodes.

In view of the earlier correlation of the observed higher saturation current with the presence of Schottky contacts, the observation of abnormal reverse $I$–$V$ behavior in the diodes with poor $I$–$V$ characteristics can be understood if the dominant reverse current under higher reverse bias is attributed to the tunneling currents through the Schottky barriers. The reasons for this conclusion are as follows. First, with $I_R$ as reverse leakage current, $T$ as temperature, $E$ as maximum electric field, and $\varepsilon$ as permittivity, the measured slopes of $I_R/T^2$ vs $E^{1/2}$ curves (0.020–0.075 V$^{1/2}$/cm$^{1/2}$) are much larger than the theoretical value 0.0044 V$^{1/2}$/cm$^{1/2}$ (at 24 °C), as calculated taking into account the lowering of the Schottky barrier height by the image force, which is given by $\Delta \phi = (qE/4\pi \varepsilon)^{1/2}$. Thus, the observed rapid increase in the reverse current with increasing reverse bias cannot be explained just on the basis of the lowering of the effective barrier height by the image force. On the other hand, the effect of temperature on the reverse $I$–$V$ curves, as shown in Fig. 4, reveals nearly athermal behavior for biases of few volts, which is considered a fingerprint of tunneling current.

The formation of small area Schottky contacts in Ti silicided $n^+/p$ diodes was also reported by Ada-Hanifi et al.\textsuperscript{10} They explained the observation of dominant tunneling currents in the same diodes in terms of the enhancement of the local electric fields (1–3 MV/cm) near the silicide spikes (200–600 Å radii). According to the criteria given by Padovani and Stratton,\textsuperscript{11} it can be shown that almost the same values (~1 MV/cm) of maximum electric field are required for tunneling current to be the dominant reverse current at room temperature in a NiSi/n-Si Schottky barrier. Such fields are very large and cannot be reached uniformly in our devices, given the doping concentration in $n$ regions (2.6 $\times 10^{17}$ cm$^{-3}$). Following the analyses of Ada-Hanifi et al. it is thus proposed that the high electric field results from the enhancement of local electric fields near individual NiSi silicide spikes that constitute the total effective Schottky areas, as calculated from the measured saturation currents (e.g., 0.066 $\mu m^2$ for the diode with the highest saturation current).

In summary, we have measured, analyzed, and compared the $I$–$V$ characteristics of $p^+/n$ diodes silicided with a pure Ni and Ni(Pt) alloy. Good $I$–$V$ characteristics were observed for all the diodes except some of the diodes Ni-silicided at 700 °C, which showed higher saturation currents as well as abnormal reverse $I$–$V$ characteristics. Experimental results show that electron diffusion current in $p^+$ region dominates the forward current in the diodes with good $I$–$V$ characteristics. In contrast, for diodes with poor $I$–$V$ characteristics, it has been concluded that both forward and reverse currents are dominated by the current that flows through Schottky contacts which are inadvertently created as a result of NiSi spikes penetrating through the $p^+$ region in the $n$ region. For diodes silicided with a Ni(Pt) alloy, all showed good $I$–$V$ characteristics without any evidence of the formation of Schottky contacts. This provides a clear evidence of enhancement of the thermal stability of NiSi due to the addition of Pt.

7. Assuming that the boron concentration $N_p$ at the edge of $p^+$ space charge region is about $3 \times 10^{19}$ cm$^{-3}$ and the effective electron diffusion coefficient $D_n$ in neutral $p^+$ region is about 3 cm$^2$/s, one obtains $W_p = 670$ Å.
9. The saturation current $I_S$ is given by $I_S = AqDnpnTW_p$, in good diodes with $D_n \propto T^3$ and $n_p \propto T^6 \exp(-E_F/KT)$. For high dopant concentration $N_n$ ($10^{18}$–$10^{19}$ cm$^{-3}$), the electron mobility $\mu_n$ is almost independent of temperature in the neighborhood of 300 °K (see Ref. 12), therefore $I_S \propto T^6 \exp(-E_F/KT)$ with $E_F$ as band gap and $\Delta$ as Boltzmann constant.