Improved Electrical Performance of Erbium Silicide Schottky Diodes Formed by Pre-RTA Amorphization of Si

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***Abstract*—Erbium silicide Schottky diodes formed on Si(001) substrate using rapid thermal annealing method show degraded Schottky-barrier height ϕ_{Beff} and ideality factor n due to the presence of silicide-induced microstructural defects which are likely sources of trap states. A method to improve the ϕ_{Beff} and n of the diodes utilizing *in situ* Ar plasma cleaning to induce a light amorphization of the Si(001) substrate is proposed. Even though the diodes formed in this way are less textured and have a poorer interface, they are free of silicide-induced microstructural defects, leading to an overall improvement in current transport and conduction properties which can be modeled using inhomogenous Schottky contact model.**

***Index Terms*—Amorphization, Erbium silicide, *in situ* plasma clean, Schottky diode, structural defect.**

I. INTRODUCTION

RARE earth silicides have drawn considerable technological interest recently for potential use as Schottky source/drain in MOS field-effect transistors (MOSFET) due to their low Schottky barriers (∼0.3 eV) to n-type Si [1]. The effective Schottky barrier height ϕ_{Beff} and ideality factor n extracted from the current–voltage (I–V) curves of Erbium silicide Schottky diodes on p-Si substrate formed using rapid thermal annealing (RTA) method have been reported to be slightly lower ($\sim \phi_{\mathrm{Beff}} = 0.7$ versus $\phi_{\mathrm{Beff}} = 0.71$eV) and much higher ($\sim n > 1.2$ versus $n < 1.1$), respectively, than that using furnace and electron beam annealing methods [1]–[3]. RTA is currently used for silicide processes because of good film uniformity and fast processing time [4]. However, it is possible that during RTA, fast reaction kinetics result in conditions favorable for microstructural defect formation [5]. These defects are suspected of being a source of leakage current. Ar plasma cleaning generally modifies the rectifying behavior of Schottky diodes due to the generation of electrically active defects by ion induced damage [6]. In this letter, we report that by using low energy Ar ions to lightly amorphize the substrate, the degree of epitaxy (or texture) of $\mathrm{ErSi_2}$ to Si(001) is reduced, removing the condition necessary for microstructural defect formation, thus improving the electrical performance of the $\mathrm{ErSi_2}$ Schottky diodes.

II. EXPERIMENT

P-type Si wafers with resistivities of 5–10Ω·cm were used as starting materials to fabricate $\mathrm{ErSi_2}$ Schottky diodes. After standard wafer cleaning, prior to Er deposition, *in situ* Ar plasma sputtering was carried out on some of the wafers by an RF Ar plasma for 120 s at a power of 100 W within the sputter chamber. A 500-Å Er layer was then sputter deposited at room temperature using a Denton Discovery sputter PVD system with a base pressure of 3×10^{-7}torr. A contact mask with 1-mm diameter circular holes was used as a physical barrier for selective erbium deposition during the sputter deposition process. A 200-Å layer of TiN was sequentially deposited without breaking vacuum to serve as a protective capping layer. Rapid thermal annealing (RTA) was then carried out with a XM80 rapid thermal annealing system using an optimized condition of 600 °C in an $\mathrm{N_2}$ ambient for 60 s. A 2000-Å layer of Au was deposited on the backside of the wafers to serve as an ohmic contact.

III. RESULTS AND DISCUSSION

Fig. 1 shows the X-ray diffraction (XRD) plots of Er-silicided Schottky diodes with (i.e., amorphized diode) and without substrate plasma cleaning (nonamorphized diode). The XRD plots show that the nonamorphized diode is highly epitaxial to the (001) plane of the Si substrate while the amorphized diode is less textured. The inset of Fig. 1 shows the cross sectional transmission electron microscopy (TEM) of the respective silicide–silicon interfaces. The nonamorphized diode [Fig. 1(a)] shows a smoother interface as compared to that of the amorphized diode [Fig. 1(b)]. However, although the nonamorphized diode has a smoother interface and is highly textured, uniformly distributed square-shaped microstructural defects with an average length of 6 μm and a density of $\sim 1 \times 10^5$ cm^{-2} can be found on the surface of the diode as seen in the inset of Fig. 1(a). These defects, absent in the amorphized diode may lead to a leakage current component which greatly increases n and reduces ϕ_{Beff}.

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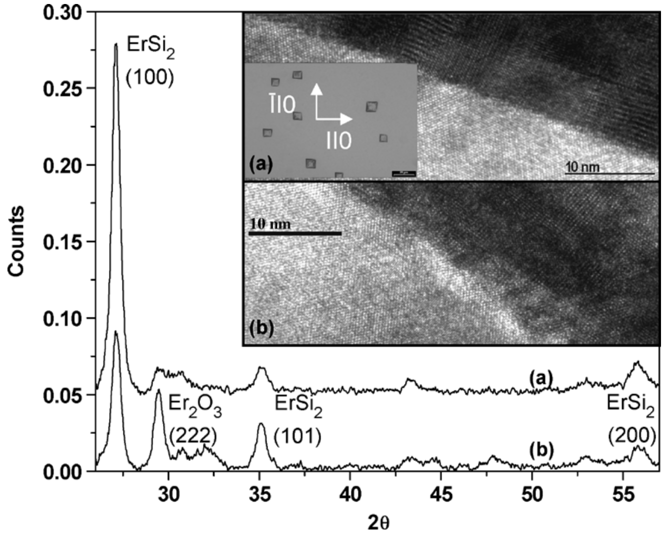

Fig. 1. Two-dimensional XRD $\theta - 2\theta$ spectrum of the $\mathrm{ErSi_2/\,Si(100)}$ diodes. (a) Nonamorphized Si(100) diode. The inset shows a bright field high-resolution TEM (HRTEM) of $\mathrm{ErSi_2/\,Si(100)}$ interface and a plane view optical micrograph of the $ErSi_2$/amorphized diodes. (b) Amorphized diode. The inset shows a bright field HRTEM of $\mathrm{ErSi_2/\,Si(100)}$ interface.

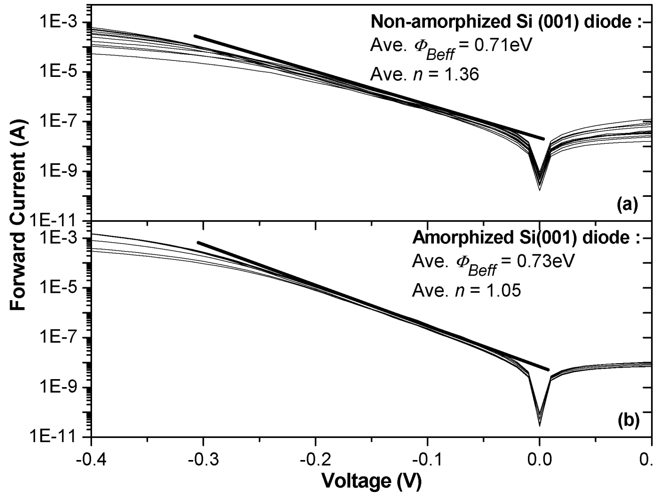

Fig. 2. I–V characteristics of $\mathrm{ErSi_2/Si(100)}$ diodes measured at room temperature. (a) Amorphized diode and (b) Nonamorphized Si(100) diode. ϕ_{Beff} and n are extracted using the TE model. The Richardson's constant used is 32 A/cm^{2}K^2 [9].

Fig. 2 shows the current–voltage (I–V) characteristics of both amorphized and nonamorphized diodes. It can be seen that the plots are almost identical and linear under forward bias (from ~0.05 V to 0.2 V). Under reverse bias, there is a considerable scatter for the nonamorphized diodes while a tightly distributed reverse current is observed for the amorphized diodes.

From the Thermionic emission (TE) theory, the diode current in the linear forward biased region is typically given by [7], [8]

$$I = AA*T^2\exp\left(-\frac{q\phi_{\mathrm{Beff}}}{kT}\right)\left(\exp\left(-\frac{qV}{nkT}\right)-1\right)$$
$$= Is\left(\exp\left(-\frac{qV}{nkT}\right)-1\right) \qquad (1)$$

where $\phi_{\mathrm{Beff}}$is the effective Schottky barrier height, k is the Boltzmann constant, T is the temperature, q is the electronic charge, A is the diode area and, A^* is the Richardson constant. The effective barrier heights and ideality factors were then extracted using (1) for typical nonamorphized and amorphized diodes, which resulted in $\phi_{\mathrm{Beff}} = 0.73 \pm 0.02$ eV and $n = 1.05 \pm 0.03$ for the amorphized diodes and $\phi_{\mathrm{Beff}} = 0.71 \pm 0.03$ eV and $n = 1.36 \pm 0.23$ for the nonamorphized diodes. The observation of an ideality factor ($n = 1.36$) much larger than unity suggests that there exists a considerable recombination current component in the nonamorphized diodes, probably due to the presence of the microstructural defects shown in Fig. 1(a). In addition, some nonamorphized diodes which are not shown in Fig. 2(a) exhibit n values close to 2. The effective barrier heights measured separately using a capacitance–voltage (C–V) method were 0.79 and 0.77 eV for the amorphized and nonamorphized diodes, respectively. These ϕ_{Beff} values are substantially higher than those extracted from I–V measurements and are believed to be due to 1) the local variation of Schottky barrier at the silicide/silicon interface and/or 2) the presence of a nonnegligible recombination current and/or other parasitic leakage components, which contribute to an increase in the apparent I_s value and consequently result in a lower ϕ_{Beff} when (1) is used for the calculation of ϕ_{Beff}.

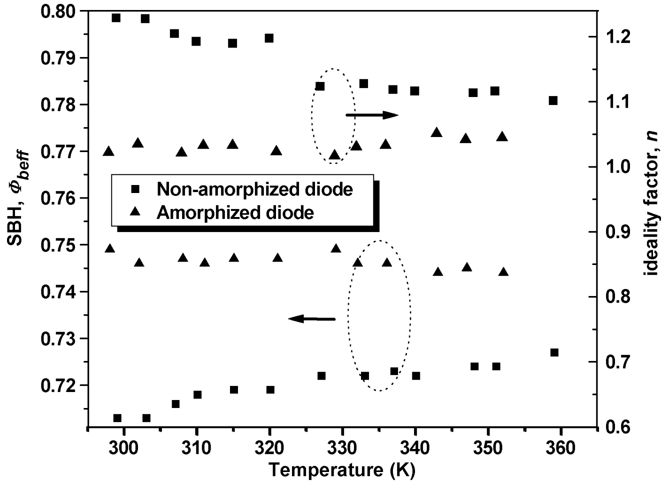

Fig. 3. ϕ_{Beff} and n extracted using TE model plotted against temperature for a typical amorphized and nonamorphized Si(001) diode. The Richardson's constant used is 32 A/cm^{2}K^2 [9].

Fig. 3 shows the temperature-dependence of ϕ_{Beff} and n values extracted using the TE model for typical amorphized and nonamorphized diodes. The amorphized diode shows a very weak dependence on temperature whereas the nonamorphized diode exhibits a strong temperature dependence. This dependence of ϕ_{Beff} and n values on temperature can be understood on the basis that there exists a dominant recombination current component for the nonamorphized diodes due to the high concentration of electrically active defects in the depletion regions of the structural defects observed. The forward current in this case can be expressed by [10]

$$I = I_{\mathrm{TE}} + I_{\mathrm{rec}} \qquad (2)$$

Thus, (1) would yield a smaller ϕ_{Beff} value and n value much larger than unity when I_{rec} is dominant at low temperatures and a more accurate ϕ_{Beff} with n close to unity when I_{TE} is dominant at high temperatures.

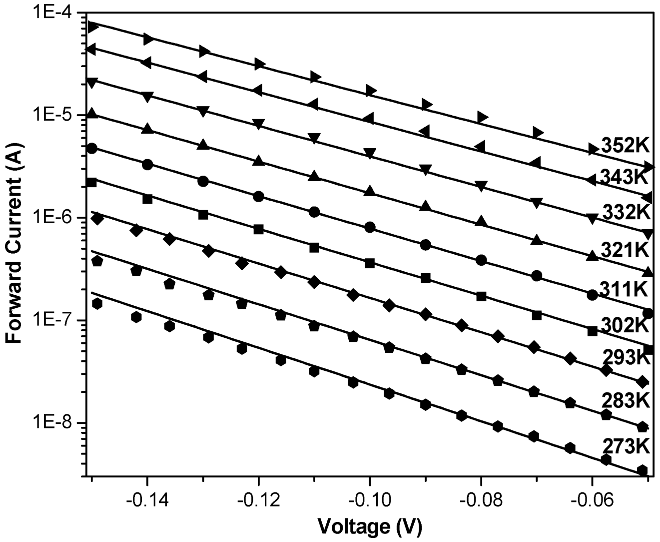

Fig. 4. I–V characteristics in the linear region of amorphized diodes at various temperatures. Solid lines were calculated using (3) with the following fitting parameters: $p_p = 2.55 \times 10^{11}$ cm^{-2}, $\sigma = 6 \times 10^{-5}$ cm$^{2/3}$V$^{1/3}$, and $\phi_{B0} = 0.76$ eV. The fitting parameters are obtained by least squares fitting of I–V curve at 273K. Subsequent fitting was done by changing the values of T from 273 to 352K. V_{bo} and N_d are obtained from $C - V$ measurement. Scatter plot represents the experimental data.

Noting that any variation in ϕ_{Beff} and n with temperature does not fit within the framework of the TE model, Tung's model of inhomogenous metal-semiconductor contacts was adopted to further analyze the diode performance. The model assumes low barrier patches with size less than the depletion width embedded in a uniformly high barrier background, leading to saddle point barriers in front of the patches which may limit the current flowing through it. The total current flowing in the linear forward biased region is [11]

$$I = AA * T^2 \exp\left(-\frac{q\phi_{B0}}{kT}\right)\left(\exp\left(-\frac{qV}{kT}\right) - 1\right) \times \left(1 + \frac{8\pi p_p \sigma^2 \eta^{\frac{1}{3}}}{9(V_{bo} - V)^{\frac{1}{3}}} \exp\left(\frac{q^2\sigma^2(V_{bo} - V)^{\frac{2}{3}}}{2(kT)^2\eta^{\frac{2}{3}}}\right)\right) \quad (3)$$

where p_p is the low barrier patch density, σ is the patch standard deviation, $\eta = \epsilon_b\epsilon_o / qN_d$ where $\epsilon_b\epsilon_o$ is the bulk dielectric constant and N_d is the dopant density of the semiconductor. V_{bo} is the band-bending of the uniform barrier outside the patches, and ϕ_{B0} is the homogenous barrier height.

Least squares curve fitting method was carried out for the linear forward biased region of the amorphized diode using (3). The results show a close fit between the experimental and simulated I–V curves as seen in Fig. 4. On the other hand, (3) does not correlate well with the data from the nonamorphized diode. This is in agreement with our argument that there exists a high concentration of electrically active defects within the microstructural defect regions which can be treated as continuous large area low barrier 'patches' and should be modeled using (2). It must be mentioned that Frenkel–Poole emission from deep trap levels in the depletion region of $\mathrm{ErSi_2}$ Schottky didoes has been proposed as a possible source of the leakage current [2].

IV. CONCLUSION

Ar plasma cleaning to induce slight substrate amorphization is proposed as a method to improve the electrical performance of erbium silicide Schottky diodes formed after RTA. This improvement is due to the removal of microstructural defects which compensates for the poorer interface, less textured $\mathrm{ErSi_2}$ film and possibly ion induced damage after the Ar plasma cleaning. The conduction mechanisms can be modeled using inhomogenous Schottky contact model.

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