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ELECTRICAL CHARACTERISTICS OF LASER-CONTACTED DIODES

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Abstract—We have fabricated p^+–n and Schottky diodes with contacts made of laser-formed palladium-silicide. The electrical characteristics of these diodes are presented. The reveise currents and breakdown voltages are comparable to conventionally contacted p^+–n diodes. The barrier height of laser-formed Schottky diodes agrees well with published values for Pd_2Si. The promising results point out the potential applications of contact formation by laser irradiation in device manufacture.

INTRODUCTION

Ohmic contacts to silicon semiconductor devices are often made of metal-silicides, due to their good adhesion to silicon and their stability under aging. In addition, silicides allow good control of the Schottky-barrier height. Metal-silicide contacts are usually fabricated by annealing metal films deposited onto the silicon substrate in a furnace flushed with an inert gas.

The formation of metal-silicide contacts by laser irradiation opens an attractive field of applications for lasers in silicon semiconductor technology. In an early publication Harper and Cohen[1] describe the preparation of p–n junctions by locally alloying Al films onto n-type Si with pulses from a Nd:YAG laser. The electrical characteristics of the diodes were poor presumably due to nonoptimal irradiation conditions.

Several recent publications describe the formation of metal-silicides by pulsed laser irradiation[2–14]. Applications of this technique to contacting and bonding of medium power silicon devices have been reported[9, 15, 16]. In these cases, however, the junction was much deeper than the thickness of the layer beneath the surface which is heated by the laser irradiation. Damage in the junction region and dopant redistribution during laser irradiation was therefore excluded. But the situation is different if diodes with shallow junctions are laser-contacted. We have therefore investigated the electrical characteristics of integrated p^+–n diodes with palladium-silicide contacts made by pulsed laser irradiation. The results are presented along with those of laser-formed Schottky diodes.

EXPERIMENTAL

Integrated p^+–n diodes were fabricated using conventional lithography and processing. The device geometry and cross-sectional view of the diodes is shown in Fig. 1. The diodes were designed with a guard ring. Two kinds of n-type ⟨100⟩ oriented Si substrates were used. One was 2 Ω cm material (Fig. 1a) and the other was epitaxial material (Fig. 1b). The epitaxial material consisted of a 0.01 Ω cm substrate with a 4 μm thick epi-layer of 10 Ω cm resistivity. Following an appropriate cleaning of the wafers an oxide layer 6000 Å thick was grown on the front side. Then windows were etched into the oxide for the guard ring diffusion. Boron was predeposited and diffused at 1050°C in a $N_2 + O_2$ mixed ambient to a depth as shown in Fig. 1. On the back side of the 2 Ωcm wafers a n^+-layer was simultaneously diffused from a phosphorous-doped CVD oxide of 3000 Å thickness. Smaller windows were then opened in

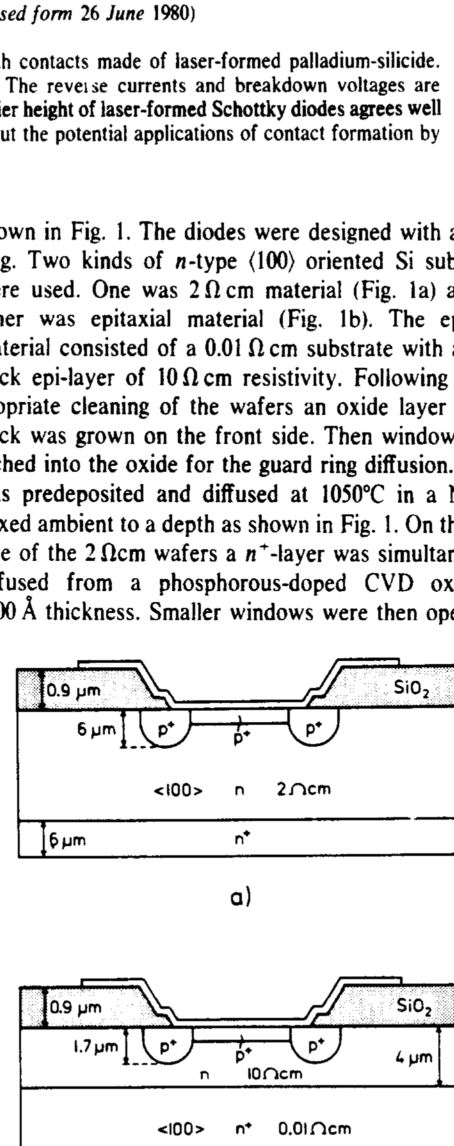

Fig. 1. Device geometry and cross-sectional view of the integrated diodes: (a) on 2 Ω cm substrate material (b) on epitaxial substrate material.

the newly grown oxide to define the diode size. Diode dia. of 100, 200 and 400 μm were chosen. A second B predeposition/diffusion formed the p^+–n junction at a depth of 1.7 μm for the 2 Ω cm substrates and 1 μm for the epi substrates. Finally a 1000 Å thick Pd layer was evaporated onto the wafers with an e-gun at pressures of about 5×10^{-8} Torr. Contact pads and connections to the diode metallizations were made by appropriately patterning of the Pd layer.

The Pd was reacted with the Si to form Pd-silicide by irradiation with a 30 ns pulse from a Nd : YAG laser. The beam spot diameter was adjusted to the diode size by varying the focal length and the laser fluence was selected by introducing neutral filters in the beam path. Reaction of the Pd with Si was detected by the characteristic color change from metallic to black after laser irradiation[3].

The entire wafer was mounted on a x–y table and each diode was individually aligned with the Nd:YAG laser with the aid of a coaxial He–Ne laser beam. In device manufacture the entire wafer would have to be aligned once with the laser using a suitable aligning pattern and the diodes could then be irradiated by a microprocessor controlled step-and-repeat process. After irradiation the diodes were tested by measuring their I/V characteristic with a Tektronix curve tracer or a ramp generator and a plotter driven by a Keithley electrometer.

RESULTS AND DISCUSSION

Typical forward characteristics of laser-contacted p^+–n diodes with a diameter of 200 μm are shown in Fig. 2. The figure includes results of diodes fabricated with the 2 Ω cm substrate as well as with the 10 Ω cm epi layer. As it is seen from Fig. 2 the diodes on the epi substrates have a much lower forward voltage drop. Since the electrical contact to the diodes was made from the contact pad on the oxide layer and from the back side of the wafer, the forward voltage drop is caused by the substrate resistance. With a specific resistivity of 2 Ω cm for the substrate material, a wafer thickness of 270 Ω cm and a diode dia. of 200 μm a resistance of 170 Ω is calculated. This value agrees well with the measured slope of 160 Ω of the diode forward characteristic. In the case of the diodes made on the epi substrate a slope of 18 Ω is obtained which corresponds well to the calculated substrate resistivity of 14 Ω. From Fig. 2 we find a turn on voltage of 0.55 V at a forward current of 0.1 mA.

Figure 3 shows the reverse characteristics of the laser-contacted p^+–n diodes fabricated with the epi substrate material. Results are given for diodes with three different diameters. The breakdown voltage varies between 30 and 40 V. This is consistent with a value of about 30 V predicted from the thickness of the epi layer and its specific resistivity. As it can be seen from Fig. 3 no systematic influence is found of the laser pulse fluence on the breakdown voltage and reverse current below breakdown. Even diodes irradiated with about 7 J/cm^2, a laser fluence which melts a layer of a thickness equal to the junction depth, show a low reverse current.

The laser-contacted diodes fabricated with the 2 Ω cm material have a much higher breakdown voltage. Measured values ranging from 150 to 180 V are consistent with a predicted breakdown voltage of 170 V. The reverse characteristics of such p^+–n diodes are given in Fig. 4. I/V curves for diodes with three different diameters are shown. The solid lines represent the reverse characteristics of the laser-contacted diodes. For comparison, some diodes were annealed in a furnace at 300°C for 30 min to form a conventional silicide contact of the composition Pd_2Si [17]. The reverse charac-

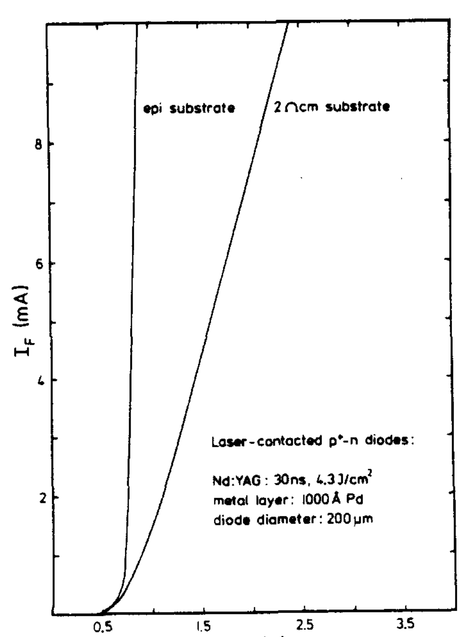

Fig. 2. Forward characteristics of laser-contacted p^+–n diodes.

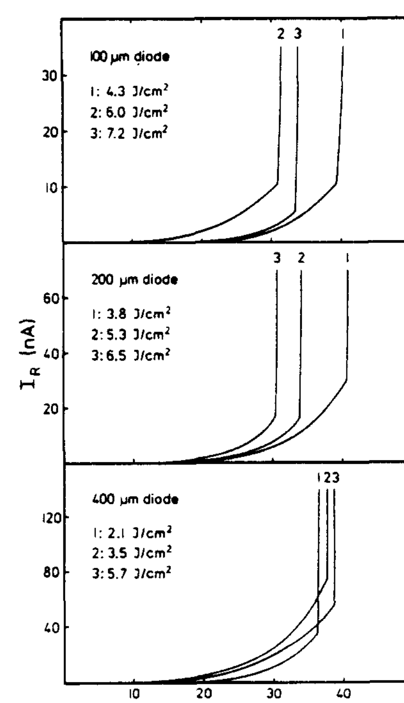

Fig. 3. Reverse characteristics of laser-contacted p^+–n diodes fabricated on epitaxial substrate material. Results are given for three different diode diameters.

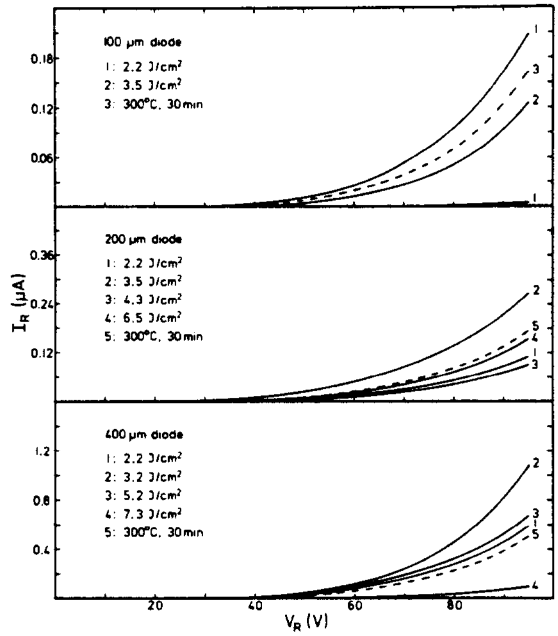

Fig. 4. Reverse characteristics of laser-contacted p^+–n diodes fabricated on $2\,\Omega\,\mathrm{cm}$ substrate material. Results are given for three different diode diameters. For comparison, reverse characteristics of furnace annealed diodes (– – – – –).

teristics of these diodes are given by the broken lines in Fig. 4. A comparison between the furnace annealed and the laser-contacted diodes shows that laser annealing had no detrimental effects on the electrical performance of the diodes. Again, no correlation is found between the reverse current at a given voltage and the laser pulse fluence (Fig. 4). Between a reverse voltage of 40 and 90 V the reverse current increases from $5\times10^{-6}\,\mathrm{A/cm^2}$ to $2\times10^{-4}\,\mathrm{A/cm^2}$. These are reasonable values for the diodes since they have not passed through special gettering processes during fabrication to improve the reverse characteristics [18].

The positive results encouraged the investigation of laser-formed Schottky diodes. Because the Schottky effect is a metal-semiconductor interface property, the preparation of such diodes with a laser pulse needs a proper choice of the laser fluence. Too high a laser fluence causes diffusion of Pd into the Si, thereby giving rise to a silicide-silicon interface with a Pd-silicide distribution resembling a diffusion profile [3]. Such an interface would destroy the Schottky effect and an Ohmic contact is obtained.

The diode geometry was the same as shown in Fig. 1(a) but without the shallow p^+-junction diffusion. The metallization was again a Pd layer 1000 Å thick. By using a low laser fluence in the range of 2–2.5 J/cm² it was possible to prepare good Schottky diodes. Figure 5 shows the forward characteristic of such diodes where the logarithm of the forward current I_F has been plotted as a function of the forward voltage V_F. The diodes have an excellent ideality factor of $n = 1.01$. An extrapolation of the straight line part of the curve to the I_F-axis yields a saturation current of $5\times10^{-6}\,\mathrm{A/cm^2}$. Therefrom it is possible to calculate the barrier height. Taking a

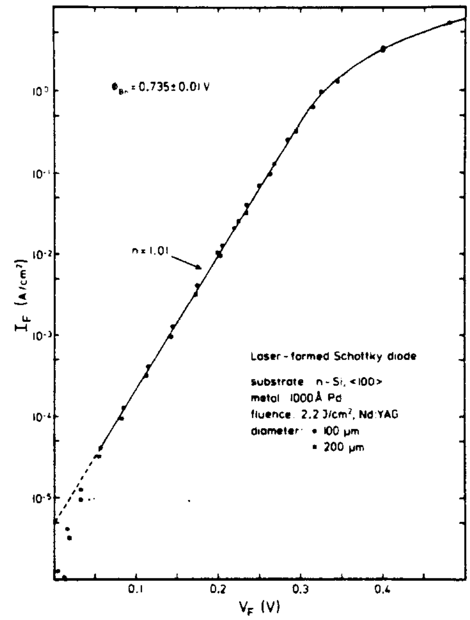

Fig. 5. Forward characteristics of laser-formed Schottky diodes.

Richardson constant of $A^{xx} = 120\,\mathrm{A/cm^2/{}^\circ K^2}$ [19] and $T = 300^\circ\mathrm{K}$ we found a barrier height of $\phi_n = 0.735 \pm 0.01\,\mathrm{V}$ for the laser-formed Schottky diodes. Though laser-formed silicides are mixtures of several metal-silicon compounds [7], the measured value of the barrier height is in agreement with published results of Pd_2Si-silicon Schottky diodes [20, 21].

Typical reverse characteristics of the laser-formed Schottky diodes are given in Fig. 6. Results are shown for two different diode diameters. Again, reverse characteristics of diodes are included in Fig. 6, where the Pd has been reacted with the silicon by annealing in a furnace at 300°C for 30 min. The comparison shows that the furnace annealed diodes exhibit a lower reverse current than the laser annealed diodes. This is due to the fact that silicide formation by annealing in a furnace is a solid state process whereas laser-formed silicides are grown from the liquid phase [2, 3]. Constitutional super-

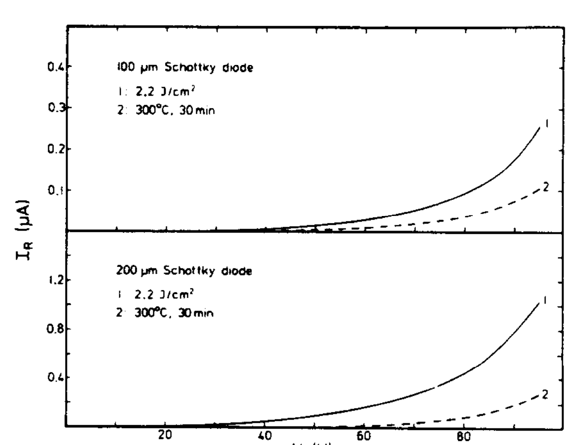

Fig. 6. Reverse characteristics of laser-formed Schottky diodes on $2\,\Omega\,\mathrm{cm}$ substrate material. Results are given for two different diode diameters. For comparison, reverse characteristics of furnace annealed diodes (– – – – – –).

cooling of the molten Pd–Si mixture may occur, which causes the growth of partially epitaxial Si columns in thin, laser-formed silicide layers, resulting in a high Si content of 80% in the silicide[8, 11]. In our case, where thick Pd-silicide layers of about 2000 Å were used, the Si content is 55% [9] and Si columns may be present to a much lesser extent. However, such columns may lead to a larger active silicide-silicon interface, giving rise to a larger reverse current at a given voltage. But besides the slightly increased reverse current the laser-formed Schottky diodes behave very well.

The reverse characteristics of the laser-formed Schottky diodes compare well with the theoretical model. Figure 7 shows a plot of the logarithm of the measured reverse current I_R as a function of the reverse voltage V_R for a 100 μm diode. The experimental data has been fitted with the eqn (22)

$$I_R = A^{**}T^2 \exp\left(-\frac{q\cdot\phi_n}{kT}\right)\exp\left(+\frac{q}{kT}\sqrt{\left(\frac{q\cdot E}{4\pi\cdot\varepsilon\cdot\varepsilon_0}\right)}\right) \times \exp\left(+\frac{q}{kT}\cdot\alpha\cdot E\right) \quad (1)$$

where the electric field E is given by

$$E = \sqrt{\left(\frac{2\cdot q\cdot N_D}{\varepsilon\cdot\varepsilon_0}\right)\left(V_R + V_{Bi} - \frac{kT}{q}\right)}. \quad (2)$$

With a donor impurity density of $N_D = 2.5\times 10^{15}\ \mathrm{cm}^{-3}$, a dielectric constant of $\varepsilon = 12$ and $V_{Bi} - (kT/q) = 0.48$ V[19] a fit was obtained with $\alpha = 38$ Å for the dipol lowering effect of the barrier height. This value is in good agreement with the values of 35 Å for RhSi and 30 Å for PtSi[22]. The active area of the diode had to be taken 1.6 times as large than the area calculated from the diameter of the diode. The larger active area can be explained by the larger silicide-silicon interface as discussed above.

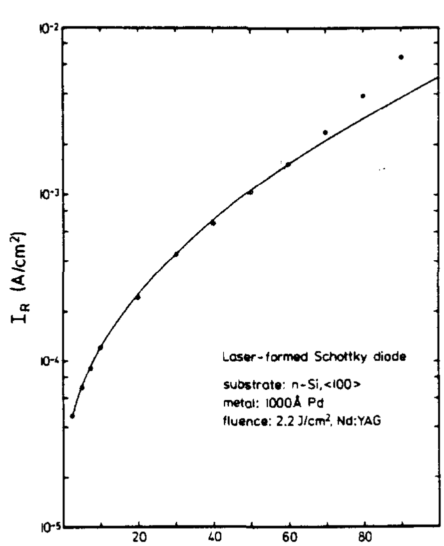

Fig. 7. Plot of the logarithm of the measured reverse current I_R as a function of the reverse voltage V_R for a 100 μm laser-formed Schottky diode. The solid line represents the fit of eqn (1) to the experimental data (· · · ·).

The deviation of the reverse current from the theoretical curve for higher reverse voltages is caused by the onset of breakdown.

CONCLUSIONS

We have demonstrated the possibility to form Ohmic contacts and Schottky barriers on Si semiconductor diodes by irradiation of the contact metal with a laser pulse. Though the melt depth caused by the laser heat pulse was equal to the junction depth in some cases, all laser-contacted p^+–n diodes showed excellent I–V characteristics. Their electrical performance is comparable to conventionally contacted diodes. It is known that laser-formed silicides have a higher electrical specific resistance than the corresponding silicides formed by annealing in a furnace[5]. Nevertheless we have not found any influence of the higher contact layer resistance on the forward characteristics when driving the p^+–n diodes with currents up to 200 A/cm². In addition, we have shown that laser-formed Schottky diodes have excellent forward characteristics. Their reverse current, however, does not quite reach the low values obtained by furnace annealing. In conclusion, it has been shown that contact formation to silicon semiconductor devices by laser irradiation gives the method potential applications in device menufacture.

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