Electrical characteristics of amorphous iron-tungsten contacts on silicon

M. Finetti,[a] E. T-S. Pan, I. Suni,[b] and M-A. Nicolet
California Institute of Technology, Pasadena, California 91125

(Received 4 February 1983; accepted for publication 22 March 1983)

The electrical characteristics of amorphous Fe-W contacts have been determined on both p-type and n-type silicon. The amorphous films were obtained by cosputtering from a composite target. Contact resistivities, $\rho_c = 1\times10^{-7}$ and $\rho_c = 2.8\times10^{-6}$, were measured on n^+ and p^+ silicon, respectively. These values remain constant after thermal treatment up to at least 500 °C. A barrier height, $\phi_{Bn} = 0.61$ V, was measured on n-type silicon.

PACS numbers: 61.55.Hg, 81.15.Cd, 73.40.Cg, 73.30. + y

Reliable metallization schemes on shallow junction devices are of great importance in semiconductor technology. The electrical characteristics of the contact and of the junction underneath may be severely deteriorated by atomic interdiffusion at the metal-semiconductor interface during post-metallization heat treatments. One way to delay the complete degradation of the contact is to use diffusion barriers.[1] For this application, metallic amorphous alloys offer an attractive alternative to their polycrystalline counterparts,[2–6] because amorphous layers do not have grain boundaries that can act as fast diffusion paths at relatively low temperatures.[7] Primary requirements for a diffusion barrier are structural and chemical stability. Low electrical contact resistivity is also required when the diffusion barrier is in direct contact with the semiconductor substrate. Amorphous iron-tungsten (Fe-W) films can be easily obtained by cosputtering from a composite target.[8] They are known to be structurally quite stable; the recrystallization temperature of tungsten-rich amorphous Fe-W films exceeds 600 °C.[8] Their electrical properties in contact with Si for diffusion barrier applications are thus of interest. In this letter we report on the contact resistivity and barrier height of amorphous Fe-W films in contact with p-type and n-type silicon.

To determine the contact resistivity ρ_c we used two different test patterns of different contact areas [Figs. 1(a) and 1(b)] on Si wafers with highly doped shallow layers; both conform to the transmission line model.[9] The p^+ layer was obtained by boron diffusion. The surface dopant concentration was $N_A \simeq 10^{20}$ atom/cm^3 and the junction depth $x_j \simeq 0.3\,\mu$m. The n^+ layer was obtained by phosphorus diffusion ($N_D \simeq 2\times10^{20}$; $x_j \simeq 0.3\,\mu$m). To prepare the test pattern shown in Fig. 1(a), long mesas were first defined in the diffusion layer by wet etching to insulate the patterns from each other. In the test pattern of Fig. 1(b), a silicon oxide layer of ~4000 Å thickness was thermally grown and diffusion windows were then opened by standard photolithography to delineate the highly doped shallow layer. In both cases, the contact pads were defined by lift-off. Before the Fe-W deposition, the samples were dipped in a 10% HF (hydrofluoric acid) solution, dried in nitrogen gas flow, and immediately loaded into the sputtering system. Fe-W was codeposited from a composite Fe/W target in a magnetron radiofrequency sputtering system with a rotating substrate table. Sputtering was carried out at 15 mTorr total pressure of argon gas and 300-W power. Fe-W films were deposited at a rate of ~200 Å/min to a total thickness of 1000 Å. An additional layer of silver of ≃2000 Å thickness was deposited on top of the Fe-W layer in the same sputtering cycle, to reduce the sheet resistivity of the contact metallization.

The amorphous structure of Fe-W was confirmed by x-ray analysis. The composition was established by backscattering spectrometry to be $\mathrm{Fe}_{0.45}\mathrm{W}_{0.55}$. The electrical resistivity of the amorphous layer was on the order of $\rho \sim 100$ $\mu\Omega$ cm.

To determine the barrier height, n-type, 1–10-Ω cm silicon wafers were used as substrates. Circular diodes of three different diameters ($d_c = 0.4$, 0.9, 2.4 mm) were fabricated by patterning of a thermally grown oxide, and by using lift-off to define metallic dots that partly overlay the surrounding oxide layer ($d_m = 0.5$, 1, 2.5 mm). In this case, the contact was formed by a ≃3000-Å-thick Fe-W film deposited by the procedure described above.

The contact resistivity measurements were first made on the test pattern of Fig. 1(a). Since the sheet resistance of the metal bilayer was low ($R_s \simeq 0.12\ \Omega/\square$), the metal pads were assumed equipotential and the values of contact resistivity were determined by using the simplified relation $\rho_c = W^2R_c^2/R_s$, where R_c is half of the resistance value measured between two neighboring pads and extrapolated to zero pad distance[9] and R_s is the sheet resistance of the dif-

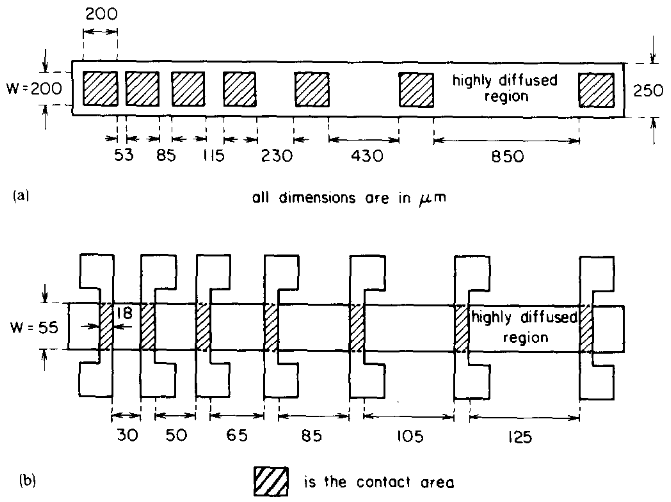

FIG. 1. Test patterns for contact resistivity measurements. (a) Highly doped region is defined by the mesa; (b) highly doped region is opened in the oxide.

---

[a] Permanent address: C. N. R./Istituto ALMEL, Via de' Castagnoli 1, 40126 Bologna, Italy.

[b] Permanent address: Semiconductor Laboratory, Technical Research Centre of Finland, Otakaari 5A, SF 02150, Expo 15, Finland.

0003-6951/83/110987-03$01.00

TABLE I. Measured contact resistivity ρ_c and barrier height ϕ_{Bn} for Fe-W contacts on silicon. ρ_c and ϕ_{Bn} of Fe and W quoted in literature are also reported for comparison.

	Contact resistivity ρ_c (10^{-6} Ω cm^2)				Barrier height ϕ_{Bn} (V)		
Heat treatment	Amorphous Fe-W on n^+-Si ($N_D = 1\times10^{20}$ at/cm^3)	Amorphous Fe-W on p^+-Si ($N_A = 1.10^{20}$)	W on n^+-Si (Ref. 15) ($N_D = 7.5\times10^{19}$)	W on p^+-Si (Ref. 15) ($N_A = 1.2\times10^{20}$)	Amorphous Fe-W	Fe (Ref. 16)	W (Refs. 17 & 18)
As-deposited	0.10 ± 0.05	2.8 ± 0.8	range from 3 to 6	range from 3 to 6	0.61 ± 0.01	0.65 ± 0.03	0.67 ≃0.64
400 °C, 30 min	0.20 ± 0.10	1.1 ± 0.3			0.65 ± 0.01[a]		
500 °C, 30 min	0.10 ± 0.05	1.1 ± 0.3					

[a] 300 °C, 30 min.

fused layer. The contact resistivity thus derived is $\rho_c = (1.4 \pm 0.4)\times10^{-6}$ Ω cm^2 for Fe-W on p^+-Si. The results for Fe-W on n^+-Si were in the same order of magnitude, but a large spread in the measured values were observed. This was attributed to values of contact resistivity which were below the sensitivity limit of this test pattern.

To improve the accuracy in the determination of ρ_c, we have used a test pattern with reduced contact area [Fig. 1(b)]. The values of ρ_c measured with this pattern are given in Table I. It can be seen that the value of contact resistivity of Fe-W on n^+-Si is one order of magnitude lower than the value obtained on p^+-Si. Furthermore, the results obtained for p^+-Si with both test patterns are in close agreement.

To check the stability of the contact we remeasured ρ_c after sequential thermal annealing in vacuum. These results are also reported in Table I. The contact resistivity remains constant after thermal annealing for 30 min up to at least 500 °C. To confirm that migration of silver does not affect the results, the measurements are repeated on samples without a silver overlayer. The increased metal sheet resistance was taken into account by applying the method given in Ref. 10. Also in this case, the contact resistivity remained stable up to 500 °C.

The barrier height of amorphous Fe-W on n-type Si was determined from the measured current-voltage (I-V) characteristics (Fig. 2). The diodes showed an average ideality factor $n = 1.08$. Due to the bulk series resistance, the straight line in the plot of $\ln I$ vs V for the forward biased diodes was limited in range, but still adequate to derive an exponential law (dashed line). The barrier height was determined from the straight line intercept at $V = 0$, assuming a Richardson constant of 112×10^4 A/m^2 K^2. As a check, the barrier height was also determined by the procedure developed by Norde.[11] For the largest area diode, only the Norde method was applied because of the more pronounced effect by the series resistance.

A barrier height, $\phi_{Bn} = (0.61 \pm 0.01)$V, was determined from the I-V characteristics and by using the Norde method. The barrier height was also determined from the reverse saturation current and agreed within measurement errors with that from the forward I-V characteristic regardless of the diode area. A slight increase in the barrier height from 0.61 to 0.65 V was observed in diodes annealed up to 300 °C. At 400 °C both ideality factor and reverse current were found to increase. The studies of metallurgical interaction between amorphous Fe-W layers and Si indicate that silicide forming reaction starts above 650 °C.[12] This does not, however, exclude the possibility of Fe in-diffusion at a level sufficient to deteriorate the electrical properties of a Schottky diode. A more careful study of this effect is presently under investigation.

By assuming $q(\phi_{Bn} + \phi_{Bp}) = 1.12$ eV, a value of barrier height of as-deposited Fe-W on p-type Si $\phi_{Bp} = 0.51$ V is derived. From the values of ϕ_{Bn} and ϕ_{Bp} and the surface dopant concentrations of our heavily doped samples, theoretical values of contact resistivity can be calculated.[13] By assuming effective masses $m_e^* = 0.5m_0$ and $m_h = 0.66m_0$

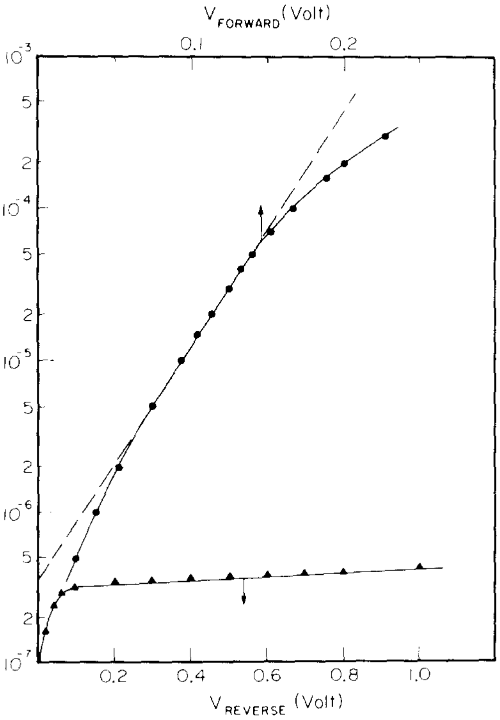

FIG. 2. Forward and reverse I-V characteristics of a Fe-W/n-Si Schottky diode. The diode area is $A = 1.26\times10^{-3}$ cm^2.

for electrons and holes, respectively, theoretical values in the order of $\rho_c = 6\times 10^{-7}\ \Omega\ \text{cm}^2$ and $\rho_c \simeq 2\times 10^{-6}\ \Omega\ \text{cm}^2$ are predicted on n^+ and p^+ silicon, respectively, This is in good agreement with the experimental results. Because tunneling is the predominant mode of current transport, these theoretical values will not change much with small changes in ϕ_{Bn}, as in fact observed (see Table I).

The contact resistivity on lightly doped n-type silicon ($N_D \sim 10^{15}$ atom/cm^3) can be easily determined also from the slope of the I-V characteristic of the Schottky diodes measured at very low voltage (< 10 mV). The measured value $\rho_c = 71\ \Omega\ \text{cm}^2$ agrees well with $\rho_c = 79\ \Omega\ \text{cm}^2$ calculated from $\rho_c = kT/qJ_s$ and the known barrier height.[14]

Table I also lists contact resistivities and barrier heights of Fe and W quoted in the literature.[15-18] The contact resistivity of W is equal to that of our amorphous Fe-W films for a comparably doped substrate. The trend for a smaller doping is as expected. The barrier heights of Fe, W, and amorphous Fe-W show a similar agreement, considering the typical uncertainties in such published values. An interesting question arising here is what the barrier height of an amorphous binary metallic layer would be when the barrier height of the constituent elements differs significantly from each other.

In summary, the contact resistivity of amorphous $Fe_{0.45}W_{0.55}$ films is $(1.0 \pm 0.5)\times 10^{-7}\ \Omega\ \text{cm}^2$ on n^+-Si and $(2.8 \pm 0.8)\times 10^{-6}\ \Omega\ \text{cm}^2$ on p^+-Si. These values stay constant after a thermal treatment for 30 min up to at least 500 °C. The barrier height of the film is $\phi_{Bn} = 0.61$ V and practically equal to that of Fe and W.

Contact resistivities $\leqslant 10^{-6}\ \Omega\ \text{cm}^2$ are of great interest in very large scale integration. However, further studies are necessary to demonstrate the barrier performance of Fe-W in a complete contacting scheme. This study is presently under way.

The authors thank Bai-Xin Liu (Caltech) for the x-ray observations, D. Rutledge (Caltech) for the access to the photolithographic facilities, and P. Iles and F. Ho (Applied Solar Energy Corporation) for supplying some of the test wafers. This work originated as a project funded by the Caltech Summer Undergraduate Research Fellowship program (F. Shair, S. P. Krown, and C. Merkel); the completion of this work was financially supported in part by the U. S. Department of Energy through an agreement with the National Aeronautics and Space Administration and monitored by the Jet Propulsion Laboratory, California Institute of Technology (D. B. Bickler).

[1] M-A. Nicolet, Thin Solid Films **52**, 415 (1978).
[2] M-A. Nicolet and M. Bartur, J. Vac. Sci. Technol. **19**, 786 (1981).
[3] K. J. Guo, J. D. Wiley, J. H. Perepezko, J. E. Nordman, D. B. Aaron, E. A. Dobisz, D. E. Madisen, and R. E. Thomas, presented at the 2nd Conf. on High Temperature Electronics and Instrumentation, Houston, Texas, December 7–8, 1981.
[4] J. D. Wiley, J. H. Perepezko, J. E. Nordman, and Kang-Jin Guo, IEEE Trans. Ind. Electron. **IE-29**, 154 (1982).
[5] B. L. Doyle, P. S. Peercy, R. E. Thomas, J. H. Perepezko, and J. D. Wiley, in *Proceedings of Materials Research Society Symposium: Interfaces and Contacts*, edited by R. Ludeke and K. Rose (North-Holland, New York, in press).
[6] W. T. Anderson, Jr., A. Christou, and J. E. Davey, Thin Solid Films (unpublished).
[7] D. Gupta, D. R. Campbell, and P. S. Ho, in *Thin Films—Interdiffusion and Reactions*, edited by J. M. Poate, K. N. Tu, and J. W. Mayer (Wiley, New York, 1978), p. 161.
[8] G. Göltz, R. Fernandez, M-A. Nicolet, and D. K. Sadana, in *Metastable Materials Formation by Ion Implantation*, edited by S. T. Picraux and W. J. Choyke (North-Holland, New York, 1981), p. 227.
[9] H. H. Berger, Solid State Electron. **15**, 145 (1972).
[10] M. Finetti, P. Ostoja, S. Solmi, and G. Soncini, Solid State Electron. **23**, 255 (1980).
[11] H. Norde, J. Appl. Phys. **50**, 5052 (1979).
[12] I. Suni, M-A. Nicolet, C. S. Pai, and S. S. Lau, Thin Solid Films (in press).
[13] A. Y.C. Yu, Solid State Electron. **13**, 239 (1970).
[14] C. Y. Chang, Y. K. Fang, and S. M. Sze, Solid State Electron. **14**, 541 (1971).
[15] V. Kumar, J. Electrochem. Soc. **123**, 262 (1976).
[16] H. Jager and W. Kosak, Solid State Electron. **12**, 511 (1969).
[17] C. R. Crowell, J. C. Sarace, and S. M. Sze, Trans. Metall. Soc. AIME **233**, 478 (1965).
[18] F. J. Landkammer, Solid State Commun. **5**, 247 (1967).