Electrical characteristics of amorphous iron-tungsten contacts on silicon

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(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, $\rho_c = 1 \times 10^{-7}$ and $\rho_c = 2.8 \times 10^{-6}$, were measured on $n^-$ and $p^+$ silicon, respectively. These values remain constant after thermal treatment up to at least 500 °C. A barrier height, $\phi_{\text{bi}} = 0.61$ eV, 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,2-4 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.4 They are known to be structurally quite stable; the recrystallization temperature of tungsten-rich amorphous Fe-W films exceeds 600 °C.5 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 $\rho_c$, 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 $N_A \approx 10^{20}$ atom/cm$^3$ and the junction depth $x_J \approx 0.3 \mu$m. The $n^+$ layer was obtained by phosphorus diffusion ($N_D \approx 2 \times 10^{20}$; $x_J \approx 0.3 \mu$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 $\sim 4000 \AA$ 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 radiofre-

![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.](image_url)
TABLE I. Measured contact resistivity $\rho_c$ and barrier height $\phi_{bn}$ for Fe-W contacts on silicon, $\rho_c$ and $\phi_{bn}$ of Fe and W quoted in literature are also reported for comparison.

<table>
<thead>
<tr>
<th>Heat treatment</th>
<th>Amorphous Fe-W on $n^+\text{-Si}$ ($N_d = 1 \times 10^{20}$ at/cm$^2$)</th>
<th>Amorphous W on $n^+\text{-Si}$ ($N_d = 7.5 \times 10^{19}$)</th>
<th>W on $p^+\text{-Si}$ ($N_d = 1.2 \times 10^{20}$)</th>
<th>Amorphous Fe-W</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-deposited</td>
<td>$0.10 \pm 0.05$</td>
<td>range from 3 to 6</td>
<td>range from 3 to 6</td>
<td>$0.61 \pm 0.01$</td>
<td>$0.65 \pm 0.03$</td>
</tr>
<tr>
<td>400°C, 30 min</td>
<td>$0.20 \pm 0.10$</td>
<td>$1.1 \pm 0.3$</td>
<td></td>
<td>$0.65 \pm 0.01^a$</td>
<td>$\pm 0.64$</td>
</tr>
<tr>
<td>500°C, 30 min</td>
<td>$0.10 \pm 0.05$</td>
<td>$1.1 \pm 0.3$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$ 300°C, 30 min.

fused layer. The contact resistivity thus derived is $\rho_c = (1.4 \pm 0.4) \times 10^{-6}$ $\Omega$ cm$^2$ for Fe-W on $p^+\text{-Si}$. The results for Fe-W on $n^+\text{-Si}$ were in the same order of magnitude, but a large spread in the measured values was 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 $\rho_c$, we have used a test pattern with reduced contact area [Fig. 1(b)]. The values of $\rho_c$ measured with this pattern are given in Table I. It can be seen that the value of contact resistivity of Fe-W on $n^+\text{-Si}$ is one order of magnitude lower than the value obtained on $p^+\text{-Si}$. Furthermore, the results obtained for $p^+\text{-Si}$ with both test patterns are in close agreement.

To check the stability of the contact we remeasured $\rho_c$ 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 $112 \times 10^4$ A/m$^2$ K$^2$. As a check, the barrier height was also determined by the procedure developed by Norde.\textsuperscript{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, $\phi_{bn} = (0.61 \pm 0.01)\text{V}$, 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.\textsuperscript{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 $g(\phi_{bn} + \phi_{Ro}) = 1.12 \text{eV}$, a value of barrier height of as-deposited Fe-W on $p$-type Si $\phi_{Ro} = 0.51 \text{V}$ is derived. From the values of $\phi_{bn}$ and $\phi_{Ro}$ and the surface dopant concentrations of our heavily doped samples, theoretical values of contact resistivity can be calculated.\textsuperscript{13} By assuming effective masses $m^* = 0.5m_0$ and $m_b = 0.66m_0$.

![FIG. 2: Forward and reverse $I-V$ characteristics of a Fe-W/$n$-Si Schottky diode. The diode area is $A = 1.26 \times 10^{-4}$ cm$^2$.](image-url)
for electrons and holes, respectively, theoretical values in the
order of $\rho_e = 6 \times 10^{-7} \ \Omega \ cm^2$ and $\rho_h \approx 2 \times 10^{-6} \ \Omega \ cm^2$ 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 theo-
retical values will not change much with small changes in
$\phi_{bn}$ as in fact observed (see Table 1).

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

Table I also lists contact resistivities and barrier heights
of Fe and W quoted in the literature.\textsuperscript{15–18} The contact resis-
tivity 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 un-
certainties in such published values. An interesting question
arising here is what the barrier height of an amorphous bina-
ry 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\textsubscript{0.45}W\textsubscript{0.55} films is $(1.0 \pm 0.5) \times 10^{-7} \ \Omega \ cm^2$ on $n^+$-Si and
$(2.8 \pm 0.8) \times 10^{-6} \ \Omega \ cm^2$ on $p^+$-Si. These values stay con-
stant after a thermal treatment for 30 min up to at least
500 °C. The barrier height of the film is $\phi_{bn} = 0.61 \ \text{V}$ and
practically equal to that of Fe and W.

Contact resistivities $<10^{-9} \ \Omega \ cm^2$ 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 un-
der 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
wafer. This work originated as a project funded by the Cal-
tech 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. De-
partment of Energy through an agreement with the National
Aeronautics and Space Administration and monitored by the
Jet Propulsion Laboratory, California Institute of Tech-
nology [D. B. Bickler].

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