Non-alloyed, Refractory Metal Contact Optimization with Shallow Implantations of Zn and Mg

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Refractory metal contacts to GaAs show great promise for stability during high-temperature processing and for high-reliability. In this paper we report a study of sputtered tungsten and tungsten silicide contacts to ion implanted p-GaAs with both Zn and Mg implantations. This study focused on refractory contacts to shallow implanted contact layers that are suitable for devices such as JFETs and HBTs. The very different energy loss mechanisms of Zn and Mg ions result in different levels of implant damage which is studied by varying anneal temperatures and measuring the effects on contact and sheet resistances with the transmission line method. For the fabrication schemes investigated, specific contact resistivity versus anneal temperature with implant doses from 1×10^{14} to $5 \times 10^{15} \text{ cm}^{-2}$ are found to vary from non-ohmic to $10^{-7} \Omega\text{-cm}^2$. Low resistance contacts to shallow ($<800 \text{ \AA}$) implanted layers are achieved.

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1. Introduction

Refractory ohmic contacts have been studied for high-speed applications such as heterojunction bipolar transistors (HBTs) and junction field effect transistors (JFETs). Tiwari *et al.* formed low resistance base contacts on HBTs by exploiting the rapid diffusion of zinc (Zn) from Zn-doped tungsten (W) into GaAs. [1] Implanted magnesium (Mg) and Zn have been studied for base contacts to both planar and mesa HBTs. [2,3] High performance enhancement and depletion mode JFETs have been fabricated by Wilson *et al.* with shallow Zn-implants and CVD-W was investigated for gate contacts [4] In this paper we report a study of sputtered W and tungsten silicide (W/Si) contacts to ion implanted p-GaAs with both Zn and Mg implantations.

This study focused on refractory contacts to shallow Zn and Mg implanted contact layers that are suitable for devices such as JFETs and HBTs. Due to the large difference in atomic masses of the ions, hence very different nuclear and electronic stopping characteristics, different fabrication schemes were required to achieve shallow, heavily doped surface layers that yielded good ohmic contacts. For the various processes considered, the specific contact resistivity and sheet resistance were determined with the transmission line method. The contact resistivity versus RTA temperature (750-900°C) with implant doses from 1×10^{14} to $5 \times 10^{15} \text{ cm}^{-2}$ are found to vary from non-linear to $\sim 1 \times 10^{-7} \Omega\text{-cm}^2$. Zn-implanted W-contacts yielded the lowest resistivity with Zn-implanted W/Si contacts roughly an order of magnitude higher in resistivity. SIMS analysis showed that low-resistance Zn-implanted contacts to shallow ($< 800 \text{ \AA}$) implanted layers can be achieved. Mg-implanted W contacts were found to ohmic, but the contact exhibits high resistivity and is not suitable for high-speed devices.

2. Experimental details

All devices for this study were fabricated by first implanting specially prepared substrates, then performing activation anneals either before sputtering or after patterning the refractory metal contacts and finally mesa-isolation of the device. Substrate preparation and implant doses for the Mg and Zn contact studies differed and are described in later sections. For the Mg-implant contact study, W-contacts with anneals both before and after W-deposition were considered.

Both W and W/Si were investigated with Zn-implanted samples. All Zn-implanted device anneals were performed after dry-etching the refractory metals. Reactive ion etching (RIE) was used to pattern all W-contacts and electron cyclotron resonance (ECR) etching was used to pattern the W/Si-contacts.

Both Zn and Mg implantations were performed with a Varian 400-10 implanter in a non-channeling direction with beam currents maintained below $1 \mu\text{A}/\text{cm}^2$ to minimize sample heating. Doses for each study are presented later. ^{24}Mg implants were performed at 45 keV through a 600 Å silicon nitride layer to place the concentration peak at the silicon nitride/GaAs interface and to yield a shallower p-layer; the mask was removed with a wet etch immediately after implantation. ^{64}Zn was also implanted at 45 keV; however, due to the shorter projected range of the heavier ^{64}Zn atom the concentration peak can be placed at ~ 230 Å from the surface without a masking layer. All implants were performed with co-implantations of phosphorus in an effort to increase the probability of Zn or Mg going on a gallium site rather than being incorporated as an interstitial. Arsenic co-implantation has been shown to be effective in achieving higher peak carrier concentrations and minimizing diffusion. [5] Equal atomic concentrations of ^{31}P were implanted with Mg and the P concentration peak is coincident with the Mg-peak. Equal doses of $^{62}\text{P}_2$ were implanted with the Zn to yield atomic concentrations of P that are twice that of Zn. Again, the P-profile was designed to overlay the Zn-profile. Rapid thermal anneals (RTA) were performed in an Addax AET RTA with ramps of $\sim 16^\circ\text{C}/\text{sec}$, hold times of 15 seconds and a cool down decay time constant of ~ 110 seconds. During anneals the samples were covered with a GaAs wafer proximity cap and rested in a silicon carbide coated graphite crucible.

Both W and W/Si were dc-sputtered in a MRC 903 sputtering system. W was sputtered to ~ 3000 Å thick with $\sim 0.7 \Omega/\text{square}$ typical sheet resistance. W/Si was sputtered from a composite target to ~ 4000 Å thick with $\sim 5 \Omega/\text{square}$ typical sheet resistance. The stoichiometry of the W/Si film was measured by RBS to be $\text{Si}_{0.3}\text{W}$. W-films were etched in a 13.56 MHz parallel plate RIE system under the following conditions: 2.5 sccm SF_6 , 10 sccm Ar, 8 mtorr total pressure, 50°C , and rf-power of 50 W which resulted in a dc-bias of -185 V. Under these conditions, ion-induced

etch damage is possible. A Plasma-Therm SLR 770 ECR system operating at 2.45 GHz was used to etch the W/Si. Ion bombardment energies were modified by superimposing an rf-signal (13.56 MHz) on the sample. Etches were performed at 20°C, 3 sccm of SF₆, 22 sccm of Ar, 1.0 mtorr, 500 W of microwave power, and 50 W of rf-power (-55 V dc-bias).

Specific contact resistivity and sheet resistance were measured using the standard transmission line method. Each device had 50 x 100 μm² contacts spaced 3, 5, 9, 13, and 20 μm apart. All reported data are averages of several devices with current-voltage linearity verified for average current densities in the implanted layer ranging from ±1200 A/cm². The reported contact resistance extracted from the measured data was limited to a minimum of 0.05 times the measured resistance for the closest spaced samples. The specific contact resistivity was calculated with the assumption that the sheet resistance under the contact is the same as in the region between the contacts.

3. Results and discussion

The specific contact resistivity of W contacts to ²⁴Mg implanted contact layers was studied with all 16 possible combinations of the following fabrication conditions: 1) ²⁴Mg implant doses of 5 x 10¹⁴ cm⁻² and 5 x 10¹⁵ cm⁻², 2) with and without a 200 Å etch before the W-deposition, 3) RTAs at 800 and 850°C prior to W-deposition 4) RTAs at 800 and 850°C after W-deposition. Since most contacts to GaAs are tunneling contacts, positioning the peak carrier concentration at the metal-semiconductor interface with the implant mask layer is expected to narrow the tunneling barrier and improve the contact. The motivation for a 200 Å pre-deposition etch is to remove implanted material that could suffer compensation by silicon driven into the GaAs from the silicon nitride during the implant. [5] Undoped, semi-insulating [100]-GaAs substrates were used in this study. Prior to implantation, the wafers were etched uniformly ~2 μm with a hydrogen peroxide-sulfuric acid etch.

Ohmic contacts were obtained with several combinations of the fabrication techniques considered. The general trends observed are as follows. Non-ohmic contacts resulted with the low dose implants except when a pre-deposition etch was not performed and the 800°C RTA was performed after W-deposition; this scheme yielded a contact resistivity 4x higher than the best

result. Ohmic contacts were realized for the high dose and lower specific contact resistivity was obtained when pre-deposition etches were performed. The lowest, and comparable, specific contact resistivities were obtained utilizing pre-deposition etches for both cases of 800°C pre-deposition RTA and 850°C post-deposition RTA. With the exception of the low dose sample discussed earlier, all other samples yielded specific contact resistivities $\geq 1 \times 10^{-2} \Omega\text{-cm}^2$. It is noted that results for the process using a high dose implant, pre-deposition etch and post-deposition RTA at 800°C is not available due to poor metal adhesion.

Sufficiently low contact resistivity for high-speed devices was not realized with non-alloyed W-contacts to shallow Mg-implanted layers. The lowest contact resistance measurement of 14 $\Omega\text{-mm}$ was obtained utilizing a pre-deposition etch and an 850°C RTA after metal deposition. This value is significantly larger than the alloyed Cr/Au contact resistivity of 1.0 $\Omega\text{-mm}$ reported by Landgren *et al.* [5]; however, a direct comparison of measured contact resistance is not valid because the implant in this work was shallower by a factor of 4 (defined by the depth at which the near surface carrier concentration is reduced by two orders of magnitude) and of lower dose yielding a higher sheet resistance. Hence, the measured contact resistivity in this work is expected to be higher due to the higher sheet resistance under the contact which was 1400 $\Omega\text{/square}$ for the 850°C-RTA contact and 4500 $\Omega\text{/square}$ for the 800°C-RTA contact. Landgren *et al.* did not report specific contact resistivity. [5] Duhamel *et al.* obtained $1 \times 10^{-5} \Omega\text{-cm}^2$ specific contact resistivity with alloyed Au/Mn contacts to GaAs implanted with multi-energy Mg-implants. [2] The lowest specific contact resistivity achieved in this work is $1.4 \times 10^{-3} \Omega\text{-cm}^2$ which is too high for high-speed electronics and higher than reported for alloyed contacts.

SIMS analysis revealed that near surface Mg concentrations were $1\text{-}2 \times 10^{19} \text{ cm}^{-3}$ which should be sufficient for realizing a low-resistance tunneling contact if the Mg is electrically activated. Duhamel *et al.* found comparable near surface atomic profiles and good agreement with measured hole profiles for five minute anneals at 750°C [2] which suggests that good activation should be obtained with the 800°C anneals considered here. Furthermore, the measured sheet resistance of 1400 $\Omega\text{/square}$ compares favorably to the Landgren *et al.* result of 300 $\Omega\text{/square}$ for thicker layers that were implanted with higher doses. [5] A possible

explanation for the higher measured contact resistance and calculated specific contact resistivity obtained here is that the combined damage at the metal-semiconductor interface due to implantation and metal sputtering may not have been annealed-out in the shorter anneal times used in this study. This finding was not investigated further because the Mg SIMS profile showed a pronounced concentration tail of the order of 10^{17} cm^{-3} to a depth of $>2000 \text{ \AA}$ which did not meet our goal of forming a heavily doped, shallow contact layer. This work does show that with phosphorus co-implantation a high surface concentration can be achieved. In addition, SIMS analyses of pre- and post-anneal profiles were essentially identical which shows that phosphorus is effective in minimizing Mg-diffusion which is similar to results reported for arsenic co-implantations. [2,6]

The specific contact resistivity of refractory metal contacts to ^{64}Zn implanted contact layers was studied with all twenty-four possible combinations of the following fabrication conditions: 1) ^{64}Zn implant doses of $1 \times 10^{14} \text{ cm}^{-2}$, $5 \times 10^{14} \text{ cm}^{-2}$ and $1 \times 10^{15} \text{ cm}^{-2}$, 2) sputtered W or W/Si contact metal, 3) RTAs at 750, 800, 850, or 900°C. Since ^{64}Zn has a much smaller projected range for a given energy, a mask layer was not required to realize a shallow implant layer. The projected range of Zn implants at 45 keV is $\sim 230 \text{ \AA}$. For this study, a $1 \text{ }\mu\text{m}$ undoped GaAs epitaxial layer was grown by MBE on a [100] semi-insulating three inch GaAs substrates in a Varian GEN-II system.

In contrast to the W-contacts on Mg-implanted GaAs, ohmic contacts were obtained for all twenty-four fabrication schemes with Zn-implantations. Furthermore, the worst W-contact on Zn-implanted layers was of lower resistance than the best W-contact on Mg-implanted material. General trends in sheet resistance and specific contact resistivity were consistent for contacts fabricated with both W and W/Si. The sheet resistance was generally observed to decrease with increasing anneal temperature and the specific contact resistivity increased with higher anneal temperatures.

In Fig. 1, the sheet resistance of Zn-implanted GaAs versus anneal temperature for devices with W-contacts is shown. For the lowest dose sample, the sheet resistance decreases by nearly a factor of 4 as the anneal temperature increases from 750 to 900°C. A smaller change is observed

for the samples implanted with higher doses and is explained by surface depletion which depletes a greater portion of the shallow implanted layer of the lowest dose samples. As the damage from implantation, metal sputtering and RIE of the W is repaired and electrical activation increases with increased annealing temperatures, the surface depletion thickness decreases and the sheet resistance decreases rapidly. For the sample implanted with a dose of $5 \times 10^{14} \text{ cm}^{-2}$, the sheet resistance is nearly constant for anneals $\geq 800^\circ\text{C}$. The sheet resistance exhibits a monotonic decrease with increasing anneal temperature for the samples implanted with doses of $1 \times 10^{15} \text{ cm}^{-2}$.

For anneals at 800 and 850°C , the sheet resistance of the two higher doses are comparable, but the highest dose has a higher sheet resistance when annealed at 750°C . This behavior is explained by greater damage occurring with the higher dose which is not repaired at the lowest anneal temperature. At the highest anneal temperature, the highest dose yields the lowest sheet resistance as expected. One expects the activation efficiency to decrease at higher doses which partially explains why the sheet resistance does not scale with dose. SIMS analysis with Cs^+ -bombardment yielded surface concentrations of $1 \times 10^{14} \text{ cm}^{-2}$, $4.7 \times 10^{14} \text{ cm}^{-2}$ and $6.3 \times 10^{14} \text{ cm}^{-2}$.

Also shown in Fig. 1 is the specific contact resistivity of Zn-implanted GaAs versus anneal temperature for devices with W-contacts. The lowest resistivity is $\sim 1 \times 10^{-7} \Omega\text{-cm}^2$ which was obtained for implant doses of $5 \times 10^{14} \text{ cm}^{-2}$ and anneal temperatures from $750\text{-}850^\circ\text{C}$. In this temperature range the highest dose yielded roughly ten times higher specific contact resistivity which suggests that implant damage is not compensated for by a higher surface carrier concentration. As shown, the resistivity increased for all implant doses when annealed at 900°C ; this is attributed to increased concentration-driven diffusion which lowers the concentration at the tunneling contact metal/semiconductor interface and an enhanced W-GaAs reaction [7]. In spite of the high sheet resistance of samples with the lowest dose, respectable specific contact resistivity for low temperature anneals are obtained.

For implant doses of $5 \times 10^{14} \text{ cm}^{-2}$ and anneal temperatures from $750\text{-}850^\circ\text{C}$ resistivities comparable to that realized with other techniques were obtained. Tiwari *et al.* diffused Zn from

the Zn-doped W with 60 second RTAs to achieve high carrier concentrations at the metal/semiconductor interface and low resistance contacts. [1] Both specific contact resistivity of $\sim 1 \times 10^{-7} \Omega\text{-cm}^2$ and corresponding normalized measured contact resistance of $< 0.1 \Omega\text{-mm}$ were found to saturate at 650°C or higher. Our specific contact resistivity is comparable, but our contact resistance of $0.2\text{-}0.4 \Omega\text{-mm}$ is higher than that obtained with Zn-diffusion which may be due to the higher concentration and lower sheet resistance obtained by Zn-diffusion. However, the measured contact resistance of $0.2\text{-}0.4 \Omega\text{-mm}$ is comparable to reported resistance of non-alloyed Ti/Au contacts to Zn-implanted GaAs. [4]

SIMS analysis showed that Zn-implantation yielded shallower contact layers after anneal than was observed in the Mg-profile. In addition, the concentration tail which was observed in the Mg-profile was not observed with Zn. Typical post-anneal Zn-profiles are approximately Gaussian and the depth at which the concentration is down by two orders of magnitude from the peak concentration is typically $700\text{-}850 \text{ \AA}$ from the surface.

In Fig. 2, the sheet resistance of Zn-implanted GaAs versus anneal temperature for devices with W/Si-contacts is shown. The general properties discussed earlier in regard to the sheet resistance characteristics of devices with W-contacts is also true for devices with W/Si contacts and will not be repeated here. Instead we will compare the sheet resistance between corresponding devices with W- and W/Si-contacts. It is noted that removal of GaAs during the both metal etches was determined to be negligible. The general trend in sheet resistance is that, within experimental uncertainty, equal or lower sheet resistance was found for samples with W/Si contacts. The difference is greatest for the lowest dose sample, but is also significant for samples with higher doses that are annealed at 750°C . One possible reason for this is that the W/Si was etched in an ECR plasma system as compared to RIE-etching of the W contact. With ECR plasma etching, the device is remote from the plasma while with RIE-etching the device is exposed to the plasma. In addition, the dc-bias is higher for RIE which enhances ion-induced damage. Depending on the etch chemistry, RIE has been shown to cause damage to depths of $100\text{-}600 \text{ \AA}$. [8] As described earlier, surface damage would be most deleterious to low dose samples which is consistent with our results. For the higher dose samples and anneal temperature

$\geq 800^{\circ}\text{C}$, the sheet resistance of the ECR-etched samples are comparable to the RIE-etched samples.

The specific contact resistivity of Zn-implanted GaAs versus anneal temperature for devices with W/Si-contacts is shown in Fig. 2. The lowest resistivity is again obtained for implant doses of $5 \times 10^{14} \text{ cm}^{-2}$; however with W/Si-contacts the minimum specific contact resistivity was $\sim 1 \times 10^{-6} \Omega\text{-cm}^2$ which is an order of magnitude higher than was obtained with W-contacts.

Furthermore the contact resistivity exhibited a rise in resistivity at a lower anneal temperature of 850°C as compared to 900°C for W-contacts. Similar to the results observed for W-contacts, at the lowest anneal temperature the highest dose is the poorest contact while at the highest anneal temperature it exhibits the lowest specific contact resistivity. The generally higher contact resistance for W/Si-contacts as compared to W-contacts is explained by an increased potential barrier at the metal/semiconductor interface which forms the tunneling contact. As the composition of Si increases to 30-40%, the barrier also increases by about 10% [9] which increases the tunneling contact resistance.

4. Conclusions

An extensive study of refractory metal contacts to GaAs implanted with either ^{24}Mg or ^{64}Zn is reported. Of the different fabrication schemes considered for W-contacts to Mg-implanted contact layers, most schemes yielded non-linear I-V characteristics and the successful ohmic contacts were high resistance contacts that are not suitable for high-speed electronics. The lowest specific contact resistivity was $\sim 1 \times 10^{-3} \Omega\text{-cm}^2$. In contrast, all of the W- and W/Si-contacts on Zn-implanted layers were ohmic and most were low resistance. The lowest specific contact resistivity of $\sim 1 \times 10^{-7} \Omega\text{-cm}^2$ was obtained with W-contacts to GaAs implanted with a $5 \times 10^{14} \text{ cm}^{-2}$ dose and annealed at temperatures from $750\text{-}850^{\circ}\text{C}$. This contact has been implemented as the gate contact in an all implanted n-channel JFET. [10] The specific contact resistivity is comparable to Zn-diffused contacts; however, the Zn-implanted contact has the advantage that a encapsulation layer is not needed to prevent Zn-contamination during subsequent processing. Contacts formed with W/Si were approximately an order of magnitude higher in specific contact resistance; this is attributed to the higher barrier in the tunneling contact formed by the W/Si- as

compared to the W-GaAs contact. The shallow contacts reported here has utility in reducing parasitics of HBTs and in improved scaling of JFETs.

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- Figure 2. Sheet resistance and specific contact resistance versus anneal temperature for W/Si-contacts on shallow Zn-implanted layers of 3 different implant doses. The uncertainties in average sheet resistance is estimated to be $\pm 10\%$ and $\pm 30\%$ in the resistivity.

Figure 1.
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Figure 2.
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