OHMIC CONTACTS TO GaAs FOR HIGH-TEMPERATURE DEVICE APPLICATIONS

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Summary

Ohmic contacts to n-type GaAs have been developed for high-temperature device applications up to 300°C. Refractory metallizations were used with epitaxial Ge layers to form the contacts: TiW/Ge/GaAs, Ta/Ge/GaAs, Mo/Ge/GaAs, and Ni/Ge/GaAs. Contacts with high dose Si or Se ion implantation (10^{12} to $10^{14}/cm^2$) of the Ge/GaAs interface were also investigated. The purpose of this work was to develop refractory ohmic contacts with low specific contact resistance (~10^{-6} Ω-cm^2 on $1x10^{17}/cm^3$ GaAs) which are free of imperfections, resulting in a uniform N^+ doping layer.

The contacts were fabricated on epitaxial GaAs layers ($n=2x10^{16}$ to $2x10^{17}/cm^3$) grown on N^+ ($2x10^{18}/cm^3$) or semi-insulating GaAs substrates. Ohmic contact was formed by both thermal annealing (at temperatures up to 700°C) and laser annealing (pulsed Ruby). Examination of the Ge/GaAs interface revealed Ge migration into GaAs to form an N^+ doping layer.

Under optimum laser anneal conditions, the specific contact resistance was in the range $1\text{-}5x10^{-6}$ Ω-cm^2 (on $2x10^{17}/cm^3$ GaAs). This is an order of magnitude improvement over thermally annealed Ag/Si[1] or Ni/Ge[2] contacts. Thermally annealed TiW/Ge had a contact resistivity of $1x10^{-6}$ Ωcm^2 on $1x10^{17}/cm^3$ GaAs under optimum anneal conditions. The contacts also showed improved thermal stability over conventional Ni/AuGe contacts at temperatures above 300°C. The contact resistivity of thermally annealed TiW/Ge does not increase appreciably with a 350°C, 190 hr anneal, while that of Ni/AuGe degrades appreciably between 25-35 hrs at 350°C. Under bias conditions (6V, 15 mA) the contact resistance of these contacts did not increase appreciably at 300°C after 160 hr. Preliminary results with the laser annealed contacts showed no measurable increase in resistance after 6 hr at 350°C.

Introduction

Low specific contact resistance ohmic contacts to n-type GaAs using epitaxial Ge films have been reported using molecular beam epitaxy[3] and vacuum epitaxy.[2,4] The epitaxial Ge film allows (in theory) the formation of contacts with a uniform N^+ layer, in the highly doped Ge film itself[3] or, from Ge doping of the GaAs.[2,4] These contacts should be more nearly free of imperfections compared to polycrystalline Ge or AuGe eutectic films in which rapid impurity diffusion occurs at grain boundaries. Both thermal annealing and laser annealing have been used to form ohmic contact. Laser annealing was used to form these contacts[5] because when a refractory metal overlayer is desired it was found[2,4] that oven anneal temperatures in the range 500-750°C were required. Subjecting the entire substrate to these high temperatures can have deleterious effects on the active and semi-insulating GaAs layers and to other metallizations previously deposited on the chip, e.g., for the purpose of fabricating integrated circuits. This problem can be obviated by selective contact annealing with a laser beam. Pulsed laser annealing may also be important in obtaining enhanced activation of implanted dopants and in obtaining certain doping profiles when rapid heating and cooling are important.

In this paper we report on TiW (88 wt. % W, 12 wt. % Ti)/Ge, Ta/Ge, Mo/Ge, and Ni/Ge ohmic contacts to n-type GaAs which have two possible areas of applications: 1) to devices which are designed to operate for extended periods of time in a high temperature ambient (above 150°C)[1], and 2) to improve the reliability of devices which experience high channel or contact temperatures, such as power field-effect transistors (FET) and transferred-electron devices (TED).[6] In both cases, local melting at imperfections in the contacts can result in device failure. Formation of an N^+ layer at the GaAs-contact interface by Ge doping can also result in significant performance gains in power FETs and TEDs through reduction in contact resistance and increased voltage levels.

Experimental Method and Results

Fabrication of the ohmic contacts was similar to that described previously.[2] A number of different types of contacts were investigated: TiW/Ge, Ta/Ge, Mo/Ge, and Ni/Ge, both with and without a high dose of Si or Se ion implanted (I^2) at the Ge/GaAs interface. Ohmic contacts were fabricated on n-type epitaxial GaAs layers with carrier a concentration of $2x10^{17}/cm^3$ grown on N^+ (100) oriented GaAs substrates doped to $2x10^{18}/cm^3$ or on GaAs epitaxial layers ($n=1x10^{17}/cm^3$, 2000Å thick) grown on semi-insulating (SI) GaAs substrates. To prepare the GaAs surface for growth of the epitaxial Ge layer, the surface was cleaned in organic solvents, etched in a solution (10 mℓ HCℓ, 10 mℓ HF, 40 mℓ H_2O, 6 drops of H_2O_2) to remove carbon and oxygen, and placed immediately into a high vacuum system. Oxides were desorbed by heating the substrate to 575°C for 15 min in a vacuum of $2x10^{-7}$ Torr. Oxide desorption was carried out at 575°C because it was found[4] by Auger electron spectroscopy (AES) that the oxide concentration was at a minimum at this temperature without greatly changing the GaAs stoichiometry. An epitaxial Ge layer was then grown in the same vacuum at 425°C to thicknesses between 200 to 2000Å by electron beam evaporation from pure Ge source. For contacts on N^+ substrates, circular Ge contact patterns (30 to 250 μm in diameter) were formed by etching and the metal overlayers were deposited to thicknesses between 1000 to 2000Å (by electron beam evaporation in the case of Ta, Mo, and Ni; and by sputtering in the case of TiW). Isolated circular contact patterns were defined using photoresist and lifting or by performing the deposition through a metal mask. Ohmic contact to the N^+ backside was made with AuGe/Ni, alloyed at 450°C for 15 sec prior to fabrication of the frontside contacts. Typical contacts are shown in Fig. 1. In the case of TiW/Ge/I^2 Si contacts to the GaAs epitaxial layer on SI substrates, transmission line model (TLM) contacts were formed by etching the mesa, TiW, and Ge in three separate etching steps.

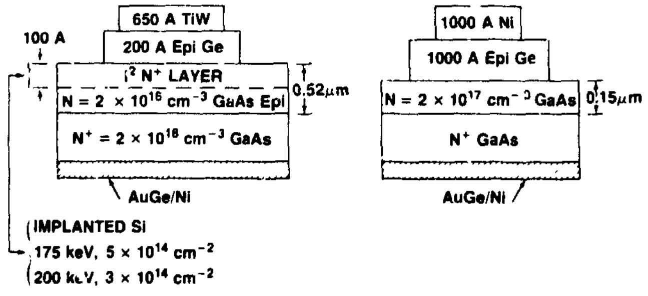
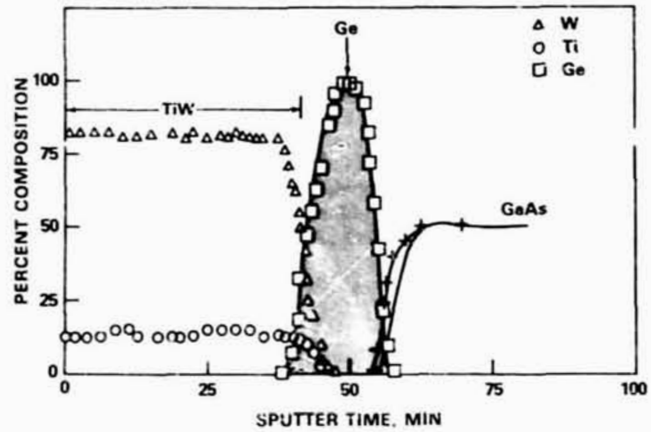
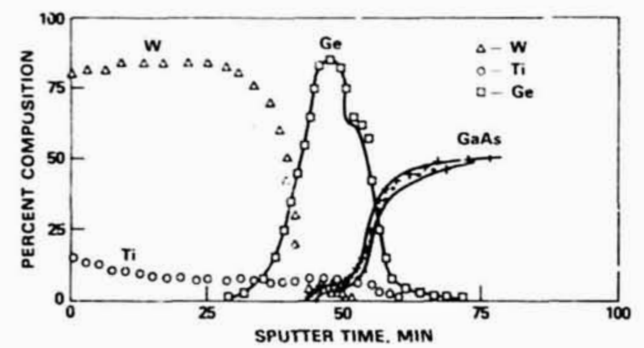


Fig. 1. Schematic cross sections of typical refractory metal/Ge ohmic contacts to GaAs.

Thermal annealing of the TiW/Ge/I^2Si contacts (1500Å TiW/400Å Ge/I^2Si at 60keV, $2x10^{14}/cm^2$) was carried out in forming gas at 700°C. Near optimum annealing conditions of 25 min, the specific contact resistance was $1x10^{-6}$ Ωcm^2 as measured by the TLM method.[8] Auger electron spectroscopy (AES) sputter profiles, as deposited and after sintering in vacuum, are shown in Fig. 2. After sintering, Ge migration into GaAs was observed indicating an N^+ doping layer at the GaAs surface. This condition is necessary for a low specific contact resistance.[9] The Si implant may also have been partially activated resulting in a further increase in the concentration of the N^+ doping layer. After 25 min at 700°C, Ga outdiffusion was also observed, allowing vacant sites for Ge or Si doping atoms.



(a)



(b)

Fig. 2. AES sputter profile of TiW/Ge/GaAs contact, (a) as deposited and (b) after ohmic contact formation at 700°C for 15 min at 10^{-9} Torr.

Laser annealing was performed with a ruby laser which emitted a one joule, 22 ns pulse obtained by Q-switching the cavity with a Pockel's cell. Experiments were performed both in single TEM_{00} mode and in multimode operation. The single mode was used for the small diameter ohmic contact experiments while the multimode was employed for large area AES analyses. For the TEM_{00} mode case, a 0.8 mm circular aperture was placed in the optical cavity. The output beam was then focused to form a 260 µm diameter spot at the sample. A 30 to 50 µm diameter spot, which contained only the center of the Gaussian beam, was obtained by use of a metal mask. Ohmic contacts were obtained at energy densities between 0.09 to 5 J/cm^2, depending on the type of contact. For the multimode case, the full one joule output was homogenized by a method similar to that described by Cullis, et al.[7] by sending it through a 1.2 cm diameter fused quartz optical wave guide which was bent and tapered to obtain a spot diameter at the sample of 0.7 cm. Although this "light guide diffuser" was effective in homogenization of the multimode structure of the beam and reducing speckle patterns, "hot spots" were still observd at the output (particularly apparent on GaAs surfaces). A detailed analysis of the appearance of hot spots will be published later.

Current/voltage (I/V) characteristics of a typical Ni/Ge contact before and after laser annealing are shown in Fig. 3 as displayed on a curve tracer. Before laser annealing the contacts were reasonably well behaved Schottky barriers; the upper curve shows a reverse breakdown voltage of about 5 volts on $2x10^{17}/cm^3$ doped GaAs. After a pulse of 0.04 J/cm^2 the rectification softens, indicating some very limited melting, perhaps associated with preferentially absorbing imperfections on the top surface. At 0.14 J/cm^2 the contact was ohmic and the photomicrograph of this contact, shown in Fig. 3, indicated very shallow, uniform melting had occurred. Similar results were found with TiW/Ge, Mo/Ge, and Ta/Ge contacts.

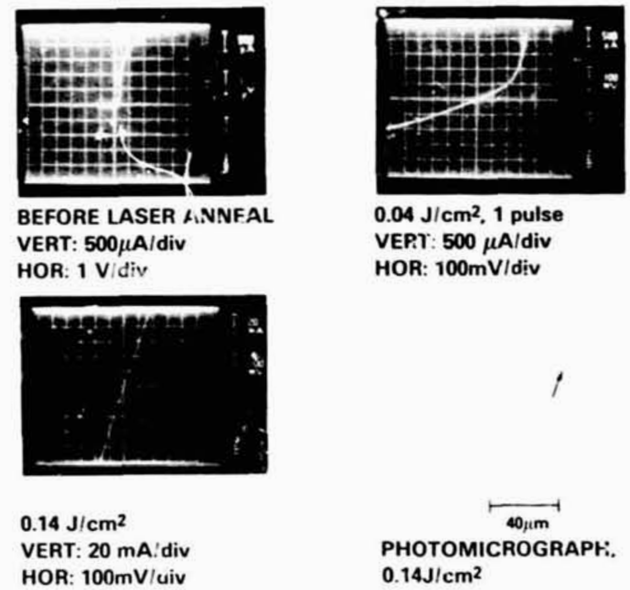


Fig. 3. Curve tracer I/V curves of Ni/Ge/GaAs contacts before laser annealing and after laser annealing at 0.04 J/cm^2 (soft Schottky barrier) and 0.14 J/cm^2 (sufficient energy density to form ohmic contact). Photomicrograph of ohmic contact after 0.14 J/cm^2.

Experimental curves of the specific contact resistance versus laser energy density are shown in Fig. 4. Measurements were made with a method similar to that of Cox and Strack.[10] These results were obtained using the TEM_{00} mode with a 30 to 50 µm diameter metal mask over (typically) 250 µm diameter isolated contacts. Approximate melting points for each of the contact types are shown at the top, as determined from photomicrographs of the irradiated surfaces. However, the melting points could not be determined precisely from the photomicrographs and very shallow melting probably occurred below these points. It was found that the contact resistivity was at a minimum near the melting point for Ni/Ge and Ta/Ge contacts. Similar TiW/Ge ohmic contacts formed on $n=2x10^{16}/cm^3$ GaAs epitaxial layers resulted in a specific contact resistance of $1x10^{-5}$ Ωcm^2. The higher value of specific contact resistance evidently resulted from the lower doping in the GaAs. Similarly, contact resistivity values for Ta/Ge, Mo/Ge, and Ni/Ge were approximately an order of magnitude higher on $2x10^{16}/cm^3$ as compared to $2x10^{17}/cm^3$ GaAs.

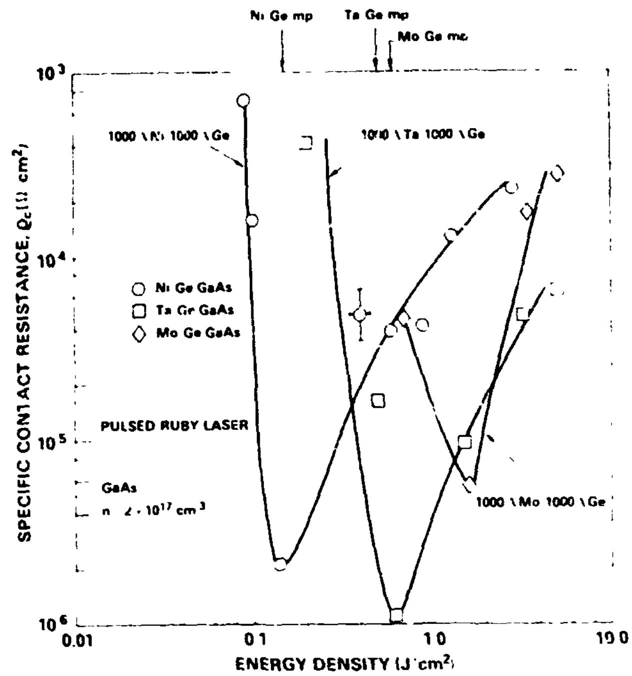


Fig. 4. Experimental values of specific contact resistance as a function pulsed ruby laser energy density; mp indicates approximate melting points as determined from surface photomicrographs.

The interfaces before and after laser annealing were investigated using AES sputter profiling techniques. Figure 5 shows AES sputter profiles of a Ni/Ge contact before laser annealing and after laser annealing at an energy density just high enough to form ohmic contact. A multimode 7 mm diameter beam was used to irradiate a GaAs sample approximately 10 mm x 10 mm containing 2000Å Ni and 2000Å Ge prepared as discussed above. At 0.10 J/cm^2 slight melting patterns could just be observed, indicating melting of the Ni and Ge just to, and including, the GaAs surface. This energy density corresponded to the threshold for ohmic contact formation. Even at this low energy density there was Ge migration into the GaAs, enough to greatly increase the n-type doping concentration at the GaAs surface. Similar profiles were observed with Ta/Ge laser annealed contacts. These profiles are also typical of Ni/Ge thermal annealed ohmic contacts studied previously.[2]

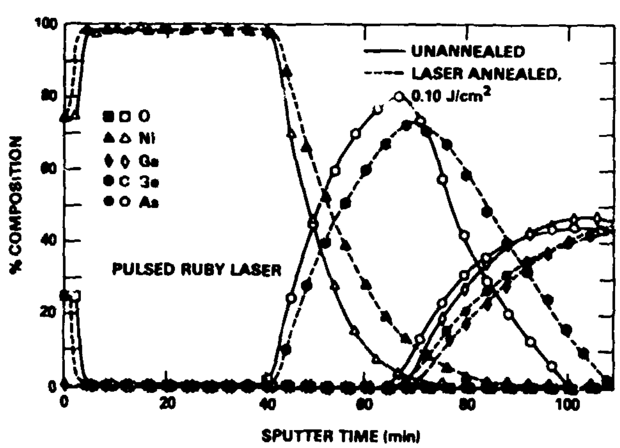


Fig. 5. AES sputter profiles of a 2000Å Ni/2000Å Ge/GaAs contact before laser annealing and after laser annealing at 0.10 J/cm^2, just at threshold for ohmic contact formation.

Discussion of Laser Anneal Results

The curves of specific contact resistance versus energy density, shown in Fig. 4, indicate there is a "window" in energy density which is appropriate for the formation of ohmic contact. This window depends on the layer thicknesses of the metal and epitaxial Ge, the pulse duration, to some extent on the surface morphology, and also on the fundamental interactions[11] of the laser beam with the overlayers and GaAs. The depth of melting and surface temperature are determined in part by the absorption coefficient, specific heat, and thermal diffusivity of the overlayers and GaAs surface. Ohmic contact appeared to occur just at the threshold of melting, but the melting must be deep enough to melt at least the top 50 to 100Å of the GaAs surface to account for the AES profiles in Fig. 5. Solid-state diffusion processes are too slow to account for these profiles. Since the heating and cooling rates are nearly the same in pulse laser annealing dominated by thermal processes,[11] the Ge migration into the GaAs surface must occur in the 50-100 ns that the surface layers are molten. A minimum in the specific contact resistance apparently occurs just above the melting point at an optimum doping level and profile. It is assumed that low contact resistance occurs by electrons tunneling between the top metal layer and the highly doped surface layer in the GaAs.[9] The specific contact resistance begins to rise at higher energy densities as the melt penetration becomes deeper and the surface temperature reaches the boiling point. Surface evaporation and oblation can then result in loss of Ge and As (as well as loss of part of the metal contact), as has been observed with these contacts at high energy densities by electron microprobe x-ray analysis. This was found to result in an increase in the specific contact resistance.

The advantages of laser annealing over thermal annealing for these particular high-temperature contacts is seen in comparison with thermal annealing results. For similar ohmic contacts, the specific contact resistance was more than an order of magnitude higher when thermally annealed[2] and high ambient temperatures (up to 650°C for 5 min) were required. The laser annealed contacts reported here also demonstrate an order of magnitude improvement in contact resistivity over Ag/Si contacts[1] thermally annealed. These contacts also compare favorably with conventional AuGe ohmic contacts, for which a specific contact resistance of 1x10^{-6} Ωcm^2 can be routinely obtained, but which degrade significantly at 350°C.

High-Temperature Aging

The TiW/Ge/I^{2}Si ohmic contacts formed on GaAs epitaxial layers on SI substrates and thermally annealed were studied by high tempeature aging in an ambient of forming gas. Figure 6 shows the change in the specific contact resistance after exposure to temperatures between 350 to 600°C for over 175 hours. The behavior of a typical AuGe/Ni contact, included in the 350°C experiments, is shown for comparison. These results demonstrate the high-temperature reliability advantages of refractory metal/epitaxial Ge ohmic contacts. With these contacts it was found that the contact resistance did not increase appreciably up to 190 hours at 350°C, while that of AuGe significantly increased between 25-35 hours at 350°C.

Preliminary high-temperature aging experiments with the laser annealed ohmic contacts (TiW/Ge/I^{2}Si, Ni/Ge/I^{2}Si, Ni/Ge, Ta/Ge, and Mo/Ge) were also carried out by aging in vacuum at 10^{-4} Torr. No measurable change in specific contact resistance was found after 350°C for 6 hr.

The thermally annealed TiW/Ge ohmic contacts were also subjected to high-temperature aging under DC bias.

Figure 7 shows the results at 300°C and 350°C after exposure for 160 hr. At 300°C the contact resistivity increased initially but stabilized at about $4\times10^{-6}\ \Omega cm^2$. At 350°C the increase in contact resistivity was much larger. This was partially explained by the large outdiffusion of Ga, shown in the AES sputter profiles in Fig. 8.

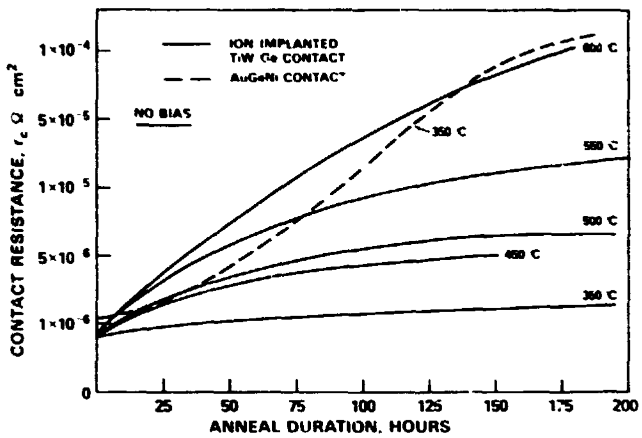


Fig. 6. Specific contact resistance of thermally annealed TiW/Ge and AuGe/Ni ohmic contacts as a function of anneal time at various aging temperatures in forming gas.

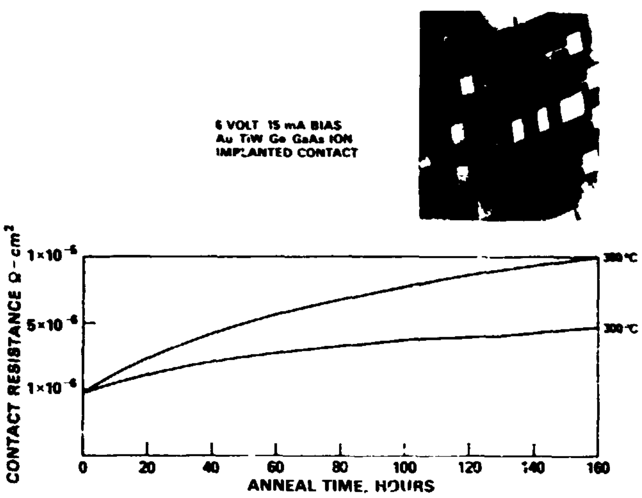


Fig. 7. Specific contact resistance of thermally annealed TiW/Ge contacts as a function of anneal time under bias conditions at 300°C and 350°C in forming gas. Test structure used to measure contact resistivity (center mesa) and to study metal migration (long arms).

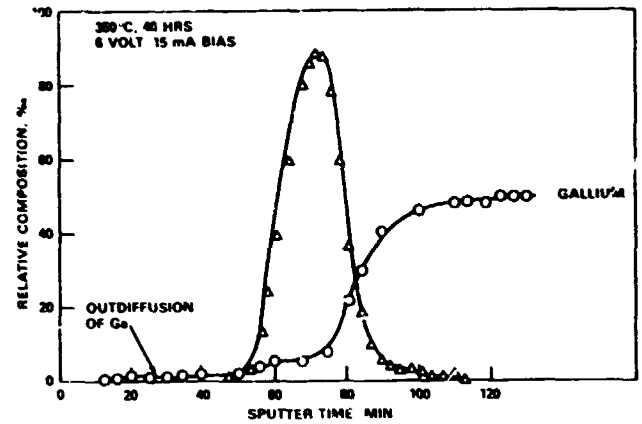


Fig. 8. AES sputter profile (Ge and Ga) of thermally annealed TiW/Ge ohmic contact after 350°C/40 hr anneal in forming gas under bias conditions, showing large Ga outdiffusion.

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