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Laser and furnace annealed Au, Ag and Al ohmic contacts on n^+ -GaAs

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Résumé. — Sur des substrats de n^+ -GaAs, des couches eutectiques de Au-Ge encapsulées avec du Ni, des couches eutectiques de Ag-Ge encapsulées de Ni et des couches eutectiques de Al-Ge ont été évaporées. Pour ces trois types de contacts, les recuits ont été effectués soit dans un four, soit à l'aide d'un laser à excimère pulsé. Les couches de Au-Ge et Ag-Ge donnent des contacts ohmiques après les deux types de recuit. Les contacts à base d'Au et recuits au laser, ont une morphologie de surface nettement supérieure et une résistance de contact quelque peu meilleure que des contacts semblables recuits avec un four conventionnel. Dans le cas des contacts à base d'argent, les échantillons recuits dans le four ont une meilleure morphologie et une résistance plus basse, que les échantillons semblables recuits au laser. Les contacts à base d'aluminium n'ont jamais donné de contacts ohmiques après un recuit thermique ; par contre, si ces contacts étaient recouverts d'une couche anti-réfléchissante, un recuit au laser donnait des contacts ohmiques, qui étaient rugueux et plusieurs fois plus résistants que les contacts à base d'or ou d'argent.

Abstract. — On n^+ -GaAs substrates, gold-germanium eutectic films with a nickel overlayer, silver-germanium eutectic films with a nickel overlayer and aluminum-germanium films were evaporated. Samples from each of these three types of contacts were furnace and laser annealed with a pulsed excimer laser for optimum results. Gold-germanium and silver-germanium films gave ohmic contacts under both types of annealing. The laser annealed gold based contacts had a better surface morphology and somewhat smaller resistance than its furnace annealed counterpart. In case of silver based contacts, it was the furnace annealed contacts that had a lower resistance and better morphology. In case of aluminum based contacts, furnace annealing did not give an ohmic contact ; with an anti-reflection coating, laser annealing gave ohmic contacts, which, however, were much more resistant and rough, compared to the gold and silver contacts.

1. Introduction.

Ohmic contact to n -GaAs is formed by evaporating an Au-Ge eutectic film on the substrate, then heating the latter in a forming gas for a few minutes at a temperature well above eutectic temperature of Au-Ge. Thus, a thin layer of GaAs melts into the alloy, and upon recrystallization on cooling, is heavily doped with Ge atoms. Usually, a thin overlayer of Ni is also evaporated on top of the Au-Ge film for better wetting to prevent « balling up », and also for dopant diffusion [1, 2].

The above process of forming Ohmic contact gives rise to surface roughness, poor edge definition and unwanted dopant redistribution — factors which will become more serious with smaller geometries in large scale integrated circuits. Laser annealing is a relatively new alloying technique, which due to its

ultrafast heating and cooling cycle, can prevent these shortcomings of furnace annealing [3-5].

Samples were prepared by evaporation of eutectic compositions of Au-Ge, Ag-Ge and Al-Ge on to n^+ -GaAs substrates through a shadow mask, then alloying these either in a furnace, or by means of a pulsed laser. Au-Ge is the most stable and common type of Ohmic contact to n -GaAs. However, its eutectic temperature at 356 °C is rather low. Ag-Ge with an eutectic temperature of 651 °C and Al-Ge with an eutectic temperature of 424 °C would be more suitable for devices operating at elevated temperatures. Silver contacts, doped with germanium [6] and, with silicon [7] have given low resistance Ohmic contacts on furnace annealing.

Samples were furnace annealed in a tube furnace with flowing gas, and also by means of a pulsed excimer laser. The laser gave a large ($3.0 \times 2.5 \text{ cm}^2$)

and uniform (better than 5 %) beam. Also at the laser wavelength of 308 nm, the reflectance of gold and silver films was much smaller than would be the case for lasers operating at longer wavelengths.

2. Experimental procedure.

Si-doped, polished n^+ -GaAs single crystals of (100) orientation and a dopant concentration of 5×10^{18} were used. These were etched in a solution of $3 \text{ H}_2\text{SO}_4 : 1 \text{ H}_2\text{O}_2 : 1 \text{ H}_2\text{O}$ for 20 s prior to evaporation. The planar contacts were formed by evaporation through a shadow mask. The mask had four rows of holes, of diameters 100 μm , 150 μm , 200 μm and 250 μm respectively. In each row, the minimum distance between two adjacent holes had the constant value of 200 μm and multiples of this value [8].

The gold, silver and aluminum eutectics were evaporated at a pressure of about 1×10^{-6} torr. The samples were either furnace annealed in a forming gas, or laser annealed in air by a single pulse from an excimer laser, operating at 308 nm wavelength and 40 ns pulse duration. The forming gas was a mixture of 15 % H_2 and 85 % N_2 .

The contacts were probed with micropositioners having Pd-tipped probes (Signatone, Inc., CA.). A constant current source and a high impedance digital voltmeter were used to determine the Ohmic nature and then resistance between contacts over a wide I - V range. The resistance between two adjacent contacts is

$$R_T = 2(R_c + R_s) + R_B + R_p.$$

In the above relation, probe resistance R_p was found out by touching the same contact with the two probes. The bulk resistance R_B was extrapolated to zero for zero contact separation. The spreading resistance R_s which is due to crowding of current lines (i.e. field not constant) is given by [6, 8].

$$R_s = \frac{\rho}{\pi d} \tan^{-1} (4 t / d)$$

where semiconductor resistivity was of the order of $10^{-4} \Omega \cdot \text{cm}$, and thickness t was half a mm. The contact diameter was d and the angle is in radians. Thus, contact resistance R_c was found out, and then specific contact resistance r_c was calculated

$$r_c = R_c \left(\frac{\pi d^2}{4} \right)$$

3. Results.

3.1 Ni/Au-Ge CONTACTS. — On clean n^+ -GaAs substrates, 1 600 Å of Au-Ge eutectic (88 % gold plus 12 % germanium by weight) film, then 400 Å of nickel film were deposited by evaporation through the mask. These were then either furnace annealed

in a forming gas at different time-temperature cycles, or laser annealed in air by single-shot pulses of 40 ns duration at 308 nm wavelength at different energy densities. The best furnace annealed ohmic contact was obtained for 4 min anneal at 450 °C, with a value of specific contact resistance $r_c = (6.7 \pm 1.3) \times 10^{-5} \Omega \cdot \text{cm}^2$. The annealing time was counted from the moment the sample was pushed into the furnace. The best laser annealed ohmic contact was obtained for an energy density of $0.5 \text{ J} \cdot \text{cm}^{-2}$, with a specific contact resistance of $(5.6 \pm 1.1) \times 10^{-5} \Omega \cdot \text{cm}^2$. In this work the aim was to compare the relative merits of different metals which could be used as ohmic contacts. So, no attempt was made to optimize the whole process to obtain the lowest possible specific contact resistance.

3.2 Ni/Ag-Ge CONTACTS. — In this case, 1 700 Å of Ag-Ge eutectic (81 % silver and 19 % germanium by weight), then 300 Å of Ni were evaporated on the substrates. Again, some of the samples were furnace annealed, others were laser annealed. The best furnace annealed ohmic contact was obtained at 600 °C for 4 min, giving a specific contact resistance of $(3.7 \pm 0.7) \times 10^{-5} \Omega \cdot \text{cm}^2$. The best laser annealed contact was obtained at an energy of $0.35 \text{ J} \cdot \text{cm}^{-2}$, corresponding to a specific contact resistance of $(9.5 \pm 2.3) \times 10^{-5} \Omega \cdot \text{cm}^2$.

The furnace annealed Ni/Ag-Ge ohmic contact at 600 °C was formed, the Ag-Ge eutectic, but by sintering at a temperature below the melting point of the eutectic. Now, at this temperature, there is in-diffusion of Ge and Ag atoms, and out-diffusion of Ga atoms. This inter-diffusion causes Ge atoms to occupy Ga sites, giving rise to an ohmic contact. The mechanism is similar to that involving sintered Pd/Ge ohmic contact on n -GaAs [9]. Sintered Ag-Ge contact at 600 °C was superior to that alloyed at 651 °C, since there was no « balling-up » ; neither was there damage to the un-encapsulated GaAs surface at this lower temperature.

3.3 Al-Ge CONTACTS. — Here, 2 200 Å of Al-Ge eutectic (47 % aluminum and 53 % germanium by weight) film was evaporated on the substrates. These were divided into three batches.

Samples in the first batch were furnace annealed in a forming gas between 300 to 500 °C. These were non-ohmic as well as highly resistive in the forward direction. Bubbles started forming on the aluminum film above 400 °C.

Samples in the second batch were laser annealed at different energy densities. However, no detectable optical or electrical changes were observed vis-à-vis an unannealed sample.

Samples in the third batch had about 500 Å SiO_2 anti-reflection coating deposited in a low temperature CVD system. The deposition temperature

was 360 °C, and the deposition rate was no more than 50 Å per min. These samples, with an AR-film, were then laser annealed at different laser energies. An ohmic contact was formed at a laser energy of 0.39 J.cm^{-2} having a specific contact resistance of $(15.1 \pm 4.2) \times 10^{-5} \Omega.\text{cm}^2$.

4. Discussion.

For Au-Ge ohmic contacts, furnace annealed, and laser annealed contacts have similar resistances within uncertainties of their values. However, laser annealed contacts have a much smoother surface morphology. Thus, laser annealed contacts will be preferable if their shelf life is as good as their furnace annealed counterparts. Figure 1(a, b) shows the optical micrographs of a furnace annealed, and a laser annealed contact respectively.

Fig. 1. — Optical micrographs of Ni/Au-Ge ohmic contacts : a) furnace annealed at 450 °C for 4 min, b) laser annealed at 0.5 J.cm^{-2} .

In case of Ag-Ge ohmic contacts, the furnace annealed ohmic contact has a lower resistance and a better morphology compared to the laser annealed contact, figure 2(a, b). Due to its higher eutectic temperature, a silver based contact will be preferable to a gold based contact at high temperature environments. However, silver oxidizes at high temperatures and is susceptible to electromigration. Reliability study should be conducted for silver contacts subjected to aging at elevated temperatures.

It is not possible to obtain an Al-Ge ohmic contact on GaAs by furnace annealing. This is due to the low solubility of Al in GaAs. Above 400 °C, the aluminum film starts to « ball up », as shown in

Fig. 2. — Optical micrographs of Ni/Ag-Ge ohmic contacts : a) furnace annealed at 600 °C for 4 min, b) laser annealed at 0.35 J.cm^{-2} .

Fig. 3. — Optical micrographs of Al-Ge contacts : a) furnace annealed at 450 °C for 4 min, b) laser annealed at 0.39 J.cm^{-2} after SiO_2 film deposition, giving ohmic contact.

figure 3(a). However, when coated with a transparent AR-film, laser annealing gave rise to Al-Ge ohmic contacts, which were rough, as shown in figure 3(b), and about three times more resistant than similar Au-Ge ohmic contacts.

5. Conclusion.

It has been shown that using a pulsed uv laser, gold, silver and aluminum based ohmic contacts can be formed on n^+ -GaAs single crystals. The latter two contacts should apparently withstand higher temperatures. However, to determine the utility of all these laser annealed contacts against the standard furnace annealed Au-Ge contact, reliability studies at elevated temperatures should be carried out, and also the distribution profiles of various constituents across metal/GaAs interface should be studied.

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