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Ohmic contact behavior of Al metal epitaxy on GaInAs by MBE

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Abstract Al metal films were grown epitaxially on $Ga_{.47}In_{.53}As/InP$ (100) by MBE. These Al films were single crystals in (011) orientation on GaInAs (001). Contrary to the common belief that Al forms a rectifying contact on this material with ~ 0.2 eV Schottky barrier height, we show for the first time that Al epilayers form ohmic contacts at room temperature on GaInAs by MBE. Specific contact resistivity of $(1.0 \pm 0.2) \times 10^{-6}$ Ω-cm^2 has been obtained with electron carrier concetration of 1×10^{16} cm^{-3} in GaInAs.

1. Introduction

Recently, there have been many reports on both GaInAs material and metal epitaxy, primarily as a result of their practical application in device engineering and metal-semiconductor interface science.

$Ga_{.47}In_{.53}As$, lattice-matched to InP, is a promising compound semiconductor with ~ 50% higher low-field mobility at 300K than GaAs (Oliver and Eastman, 1980). Its bandgap of 0.75 eV (1.65 µm) is of interest in optical communication. This confirms its broad optoelectronic application (Pearsall et al, 1981, Gammel and Ballantyne, 1980). InGa is also a favorable choice for high speed devices, because intervalley-scattering energy, Γ-L valley separation (which limits the applied electric field and hence operating speed) 0.55 eV, c.f. 0.31 eV for GaAs. (Cheng et al, 1982, Eastman, 1981)

Metal epitaxy on III-V compound has also attracted different research interests. Single crystal Al epitaxially grown on GaAs (001) with Al growth plans parallel to the GaAs (001) or (011) showed ideal Schottky-barrier diode characteristics (Ludeke et al, 1973, Cho and Dernier, 1978, Petroff et al, 1981). However (011) orientated Al epilayers grown in-situ on InP (001) by MBE showed interesting I-V charateristics with reduced Schottky barrier height, i.e. 0.1 eV at 77^oK and ohmic behavior at R.T. (Sullivan et al, 1980). A similar phenomenon was first discovered in Ag ((011)-single crystal orientation) and Au ((001-single crystal orientation) epitaxial films grown onto Ar-ion bombarded and thermally annealed InP (001) substrates (Farrow 1978). More of this metal contact behavior was discussed in cases of reactive (Al, Ni, Fe) and unreactive metals (Au, Ag, Cu) deposited on cleaved InP (011) surfaces. Reactive metals deposited on clean surfaces as well as metals on oxygen, chlorine or air, exposed InP surfaces, all exhibited reduced Schottky-barrier height of much less than 0.1 eV i.e. ohmic contact (Williams et al, 1979).

Such interesting contact behavior was discovered for the first time in ternary compound GaInAs in this work, where (011) oriented single crystal Al was grown onto $Ga_{.47}In_{.53}As$/InP(001) by MBE. Metal Schottky barriers on $Ga_{.47}In_{.53}As$ have long been known to be about 0.2 eV (Kajiyama et al 1973). In contract the present work shows that single crystal Al forms ohmic contacts on $Ga_{.47}In_{.53}As$ at room temperature and only slight rectification at 77°K. Ohmic contact resistivities of $\sim 1 \times 10^{-6}$ Ω-cm^2 have been obtained. This result demonstrates the practical practical non-alloyed ohmic contacts formed in-situ on GaInAs by metal beam epitaxy.

2. Experiments and Results

2.1 Sample Preparation and Growth

Standard solvent cleaning and etching (in 8:1:1 H_2SO_4::H_2O_2:H_2O) processes were applied to InP (001) substrates before loading into the MBE chamber. $Ga_{.47}In_{.52}As$ films were grown on (001) InP at 505°C to 515°C under As-stabilized growth conditions with beam-equivalent-pressure ratio of group V to group III (P_{BE}^{V}/P_{BE}^{III}) ~ 40-45. Good lattice matched films were usually obtained; $(\Delta a/a) \geq 7 \times 10^{-4}$ or composition variation > 1% and shown by x-ray rocking curves.

In this study more than 45 in-situ Al single crystal films were grown on GaInAs under various growth conditions. (a) deposition under background As_4 pressures from 4.0×10^{-8} to 2.0×10^{-9} Torr; (b) substrate temperature (T_S) during deposition (T_{Sub}^{Al}): ranged from 45°C to 240°C; (c) Al beam flux, from 0.4 to 9 monolayers/sec; (d) T_S when As beam was shuttered after GaInAs growth (T_{Sub}^{As}): from 200°C to 470°C; (e) Al films were also grown on both As-stabilized and metal-stabilized surfaces. Metal-stabilized surfaces of GaInAs were obtained by heating until reflection electron diffraction patterns changed from 2x4 to c(8x2) then cooling to Al deposition temperature.

2.2 Crystallinity of Al film

It has been demonstrated that Al can be grown epitaxially to GaAs with lattice mismatch of 1.3%, so could Al be grown epitaxially on GaInAs with lattice mismatch of 2.4%? Beside the streaked RHEED, patterns, x-ray diffractometry also verified the crystallinity and orientation of Al epi-layers on GaInAs. In Fig. 1 the Al (220) peak stands out from GaInAs/InP (200) $K_{\alpha 1}$ and $K_{\alpha 2}$ signals. In this case of GaInAs lattice-matched to InP, x-ray diffraction is not able to be distinguished one from the other. Also Al $K_{\alpha 1}$ and $K_{\alpha 2}$ signal are not resolvable, due to either the non-perfect crystalline structure or defocusing x-ray beam on the Al film. Table 1 summarizes all the resolvable lines of x-ray angular spectrum. From this table it can be concluded that Al(011) single crystal planes can be grown epitaxially on GaInAs/InP (001).

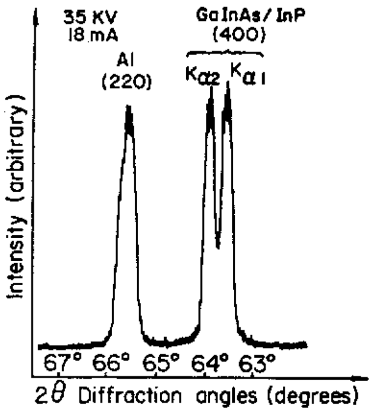


Fig. 1. X-ray diffractometer spectrum for Al/$Ga_{.47}In_{.53}As$/InP (001), (x-ray power 34 kV, 18 mA).

(hkl) / 2θ(°)	GaInAs/InP	Al	Relative intensity %
27.98	(200), Kβ		45
30.8	(200), K_{α_1}		100
31.6	(200), K_{α_2}		98
57.1	(400), Kβ		40
58.7		(220), Kβ	5
63.65	(400), K_{α_1}		98
64.1	(400), K_{α_2}		94
65.65		(220), K_α	92
91.95	(600), Kβ		5
104.2	(600), K_{α_1}		85
104.6	(600), K_{α_2}		43

Table I. X-ray diffraction lines and their identification with Al and GaInAs crystal planes.

2.3 Electrical Characteristics

I-V curves of Al(011)/GaInAs(001) Schottky diodes on conductive InP substrates are shown in Fig. 2(a,b). These typical samples show that contacts are ohmic at room temperature and slightly rectifing at 77K. In contrast Al,Ag and Au Schottky contacts on GaInAs evaporated outside the MBE system show ideal rectifying diode behavior in Figs. 2(c) and (d). (Au and Ag have similar I-V's and are therefore not shown).

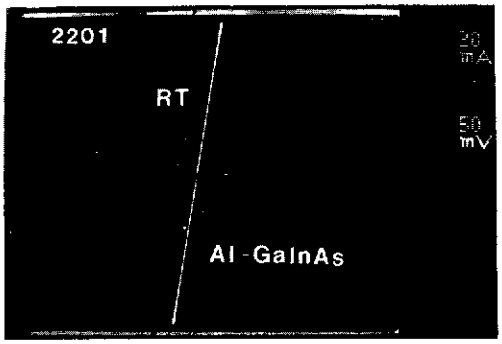
Schottky barrier heights can be obtained by assuming thermionic emission of carriers over the barrier. Barrier height is then given by

$$\phi_{BO} = \frac{kT}{q} \ln \left|\frac{A^{**}T^2}{|I_o|}\right|,$$

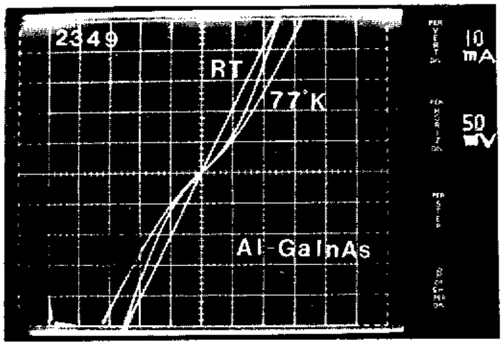
$|I_o|$ is the vertical intercept of $\ln|I|$ vs V, applied voltage, at V = 0 or can be estimated from reverse saturation current.
Hence we obtain

ϕ_{BO} (Ag) = 0.27 eV, ϕ_{BO} (Au) = 0.25 eV and ϕ_{BO}(Au) = 0.22 eV.

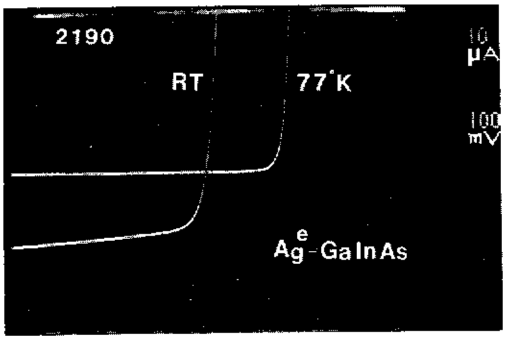
These values are close to what would be expected (Kajiyama et al 1973). No correlation between ϕ_{BO} and work function of metals could be found in this work.



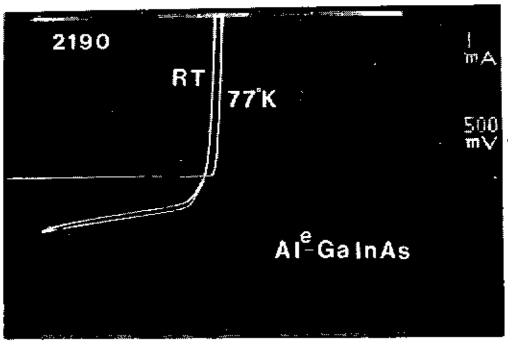
(a) #2201: Typically good ohmic I-V 300°K for single crystal Al on GaInAs (001). Current on vertical scale is 20mA/div; voltage on horizontal scale 50mV/div.



(b) #2349: Ohmic I-V at room temperature and non-ohmic IV at 77°K. The trace in the middle is I-V for 77°K<T<RT..



(c) #2190: Ag on GaInAs (evaporated outside MBE chamber).



(d) #2190: Al on GaInAs (evaporated outside MBE chamber) which is the same substrate as the one used for Ag as well as Au evaporation.

2.4. TLM (Transmission Line Method) Contact Measurement

TLM contact patterns (Berger 1972) were formed on single crystal Al ohmic contact on GaInAs on S.I. InP substrates by standard optical lithography techniques followed by mesa etching down to the GaInAs layers to reduce possible fringing effects. Contact resistivity can be obtained by the formula

$$\theta_c = R_S L_T^2 \text{ , if } L_T << L_{\text{(Length of pad)}}$$

Both R_S (sheet resistance) and L_T (transfer length) can be obtained from the R-L plot, as clearly shown in Fig. 3. The contact resistance in Fig. 3 is actually corrected for the probe resistance by

$$R_T = 2R_p + 2R_c + R_S \frac{L}{W} \text{ , } R_p \text{ is the probe resistance}$$

Probe resistance is measured to be 0.5 Ω per probe in this case. Contact resistivity of these Al/GaInAs contacts varies from mid 10^{-4} Ω-cm^2 to low 10^{-6}Ω-cm^2 even to high 10^{-7} Ω-cm^2. With contact resitivity as a measure, optimum growth parameters are obtained as in Table 2.

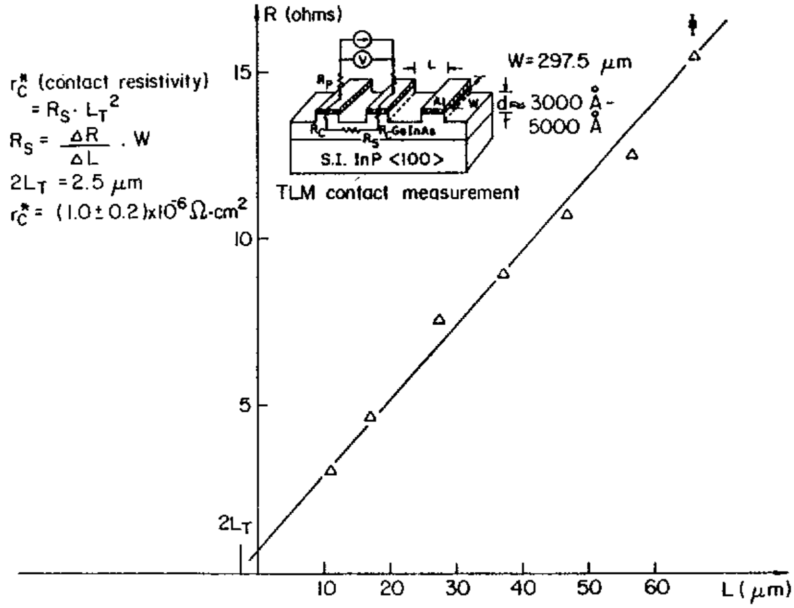


Fig. 3. TLM contact measurement (see insert). L(μm) is the contact separation and R is the measured resistance between contact pads. $2L_T$ is the horizontal intercept as R → 0.

For optimum low contact resistivity, Al beam epitaxy should be carried out under the following conditions: (a) low background As pressure; (b) As-stabilized GaInAs surface before Al deposition; (c) high Al beam flux at least greater than monolayer/sec; (d) T_{sub}^{Al} is critical; high temperature tends to enhance island growth and ends up with large grain sizes, even a rectifying contact at T_{sub}^{Al} ~ 240°C; (e) There is a trend that at high T_{sub}^{As}, r_c will increase.

Background pressure during deposition	$\lesssim 10^{-8}$ torr
Final surface structure of GaInAs, before deposition	r_c (As-Stab.) < r_c (Metal-Stab.)
Al beam flux (deposition rate)	$P_{BE} \gtrsim 2.5 \times 10^{-7}$ torr; $F \gtrsim 1.5 \times 10^{15} \frac{\text{atoms}}{\text{cm}^2\text{-sec}}$ ($\gtrsim$ 1 monolayer / sec)
Substrate temperature during deposition	$T_{sub}^{Al} \lesssim 150\,°C$
Substrate temperature when As-beam shuttered	$T_{sub}^{As} \lesssim 430\,°C$

Table 2. Optimum conditions for good Al non-alloyed ohmic contact by MBE are listed.

2.5. Doping and Annealing Effect

Increased doping level in GaInAs film causes contact resistivity to decrease. Generally a N_d^{-1} relationship, is followed (see Fig. 4). Annealing of Al on GaInAs lowers contact resistivity. r_c decreases by about an order of magnitude, from 8.9 x 10^{-5} Ω-cm² to 9.5 x 10^{-6} Ω-cm², for samples annealed at 240°C for 1-1/4 minutes. It was also observed that resistivity decrease as annealing time was increased. Both annealing temperature and time effects are shown in Fig. 5.

3. Discussion and Conclusion

It has been demonstrated that single crystal Al forms ohmic contact on $Ga_{.47}In_{.53}As$/InP(001) by MBE, with low ohmic contact resistivity in the range of low 10^{-6} Ω-cm². This interesting phenomenon can be tentatively explained by the reactive nature of Al metal on GaInAs. ($\Delta H_R < 0$). In similar cases of reactive metals (Al,Fe or Ni) on InP (Williams, 1979), the contacts also exhibited reduced barrier phenomena ($\phi_B \lesssim 0.1$ eV). Due to the lack of chemical information at this point, no conclusion can be drawn concerning the possibility of depletion of As on the surface layers of GaInAs or diffusion of species across the interface. It is equally possible that Al forms Schottky ohmic contact on GaInAs, because electron affinity of $Ga_{.47}In_{.57}As$ is about 4.5 ~ 4.6 eV and work function of Al, 4.2 eV.

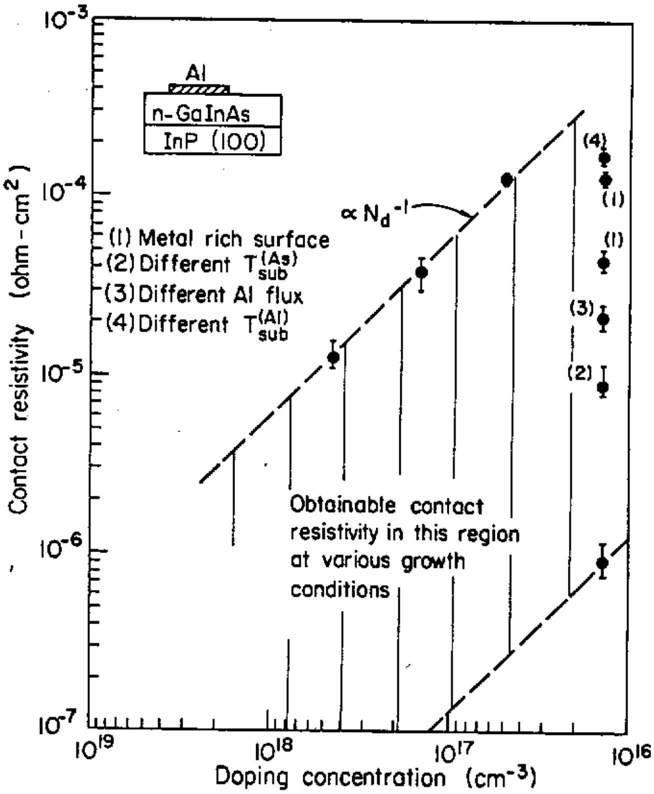


Fig. 4. Doping effect on contact resistivity is plotted as resistivity against n-type doping level (N_d) in GaInAs. It shows that resistivity follows N_d^{-1}. Also shown in figure are resistivity under other growth conditions. Shaded area is the region of expected obtainable resistivity.

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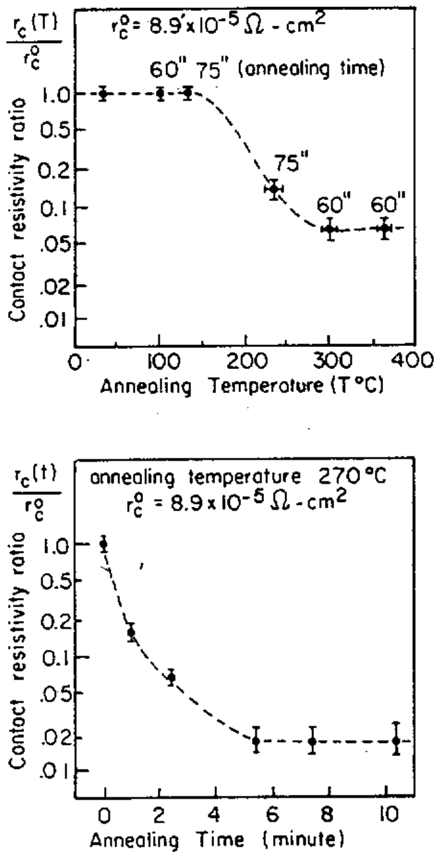

Fig. 5. Annealing temperature effect is shown in the upper diagram; annealing time effect, below. Saturation of annealing effect is also observed.

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