In-situ and *Ex-situ* Ohmic Contacts To Heavily Doped p-InGaAs

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Very low resistance metal-semiconductor contacts are crucial for the performance for THz-bandwidth transistors. $\rho_c < 1\times10^{-8}\ \Omega\text{-cm}^2$ is required for III-V HBTs and FETs for having simultaneous 1.5 THz f_t and f_{max} [1, 2]. We had earlier reported low resistivity *in-situ* ($\rho_c = 1.1\times10^{-8}\ \Omega\text{-cm}^2$) [3] and *ex-situ* ($\rho_c = 1.4\times10^{-8}\ \Omega\text{-cm}^2$) [4] ohmic contacts to n-$In_{0.53}Ga_{0.47}As$; contacts of similar resistivity to p-$In_{0.53}Ga_{0.47}As$ are required for several InP-based devices, most particularly for the base contacts of HBTs [5, 6]. Low resistivity is less readily obtained for *ex-situ* contacts than it is for *in-situ* contacts, as semiconductor surface oxides must be removed prior to metal contact formation. While some device fabrication processes allow *in-situ* p-semiconductor-metal contact formation, common HBT fabrication processes force base contact formation after the semiconductor surface is exposed to air, hence low-resistivity *ex-situ* contacts are required. *Ex-situ* Pd/Ti/Pd/Au contacts have shown $\rho_c = 4\times10^{-8}\ \Omega\text{-cm}^2$ to p-$In_{0.53}Ga_{0.47}As$ [6, 7]. Here we report record low contact resistivities of $\rho_c = (1.0\pm0.7)\times10^{-8}\ \Omega\text{-cm}^2$ and $(1.5\pm0.9)\times10^{-8}\ \Omega\text{-cm}^2$ to p-$In_{0.53}Ga_{0.47}As$ obtained by *in-situ* and *ex-situ* techniques, respectively, using iridium (Ir) contact metal.

The semiconductor epilayers were grown by solid source MBE. A 100 nm undoped $In_{0.52}Al_{0.48}As$ layer was grown on a semi-insulating InP (100) substrate, followed by 100 nm of carbon doped $In_{0.53}Ga_{0.47}As$, using CBr_4 as the dopant source. The $In_{0.53}Ga_{0.47}As$ layer was grown at 350 ^oC substrate temperature and a 12:1 groupV to groupIII ratio. Ir (20 nm) and Mo (20 nm) were deposited *in-situ* on half the wafer surface in an electron beam evaporator attached to the MBE chamber under ultra high vacuum (UHV). The wafer was removed from vacuum and cleaved; the piece having *in-situ* Ir/Mo metal is the *in-situ* sample; the piece having a bare $In_{0.53}Ga_{0.47}As$ surface is the *ex-situ* sample.

The *ex-situ* sample was exposed to UV-ozone for 30 minutes and then treated with 1:10 $HCl:H_2O$ and a DI rinse for 1 minute each. It was then loaded in the MBE chamber, cleaned with atomic hydrogen at 65 ^oC for 30 minutes, and annealed at 450 ^oC for 10 minutes in a separate chamber connected under UHV. After this anneal, the RHEED pattern showed a clear (3×2) reconstruction. Ir (20 nm) and Mo (20 nm) were then deposited in the electron beam evaporator connected under UHV.

Both *in-situ* and *ex-situ* samples were processed into transmission line model (TLM) structures for contact resistance measurement. Ti (20 nm)/Au (500 nm)/Ni (50 nm) contact pads were patterned on the samples using photolithography and lift-off after an e-beam deposition (Fig. 1). Ir/Mo was then dry etched in SF_6/Ar plasma using Ni as a mask. Resistance was measured by four-point (Kelvin) probing using separate pads for current biasing and voltage measurement (Fig. 2). The processed samples were annealed under nitrogen atmosphere at 250 ^oC for 60 minutes, replicating the thermal cycle experienced by a base contact during heterojunction bipolar transistor fabrication.

As determined through Hall measurements, the hole concentration, mobility and sheet resistance on the as-grown $In_{0.53}Ga_{0.47}As$ sample were $1.5\times10^{20}\ \text{cm}^{-3}$, 27.1 cm^2/Vs and 164.8 Ω/□, respectively. Figure 3 shows the variation of measured TLM resistance with gap spacing for the *in-situ* and *ex-situ* samples. The ρ_c achieved for the un-annealed *in-situ* and *ex-situ* samples were $(1.0\pm0.6)\times10^{-8}\ \Omega\text{-cm}^2$ and $(1.5\pm0.9)\times10^{-8}\ \Omega\text{-cm}^2$, respectively, these being the lowest reported to date for contacts to p-type $In_{0.53}Ga_{0.47}As$. Contact resistivities of the *in-situ* and *ex-situ* annealed samples were $(1.2\pm0.7)\times10^{-8}\ \Omega\text{-cm}^2$ and $(1.8\pm0.9)\times10^{-8}\ \Omega\text{-cm}^2$, respectively, differing from the pre-anneal data by less than the precision in measurement. These ultra low contact resistivities make Ir a strong candidate for p-type contacts in THz HBTs.

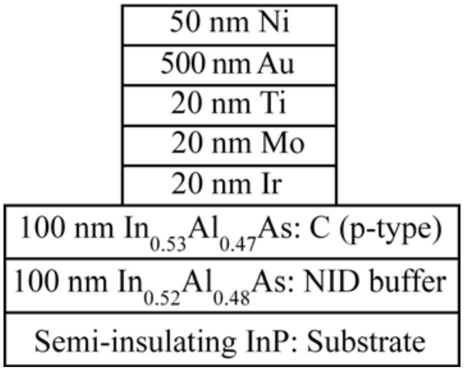

Fig 1: Cross-section schematic of the metal-semiconductor contact layer structure. Ir and Mo were deposited in an electron beam deposition chamber connected to MBE system under ultra high vacuum.

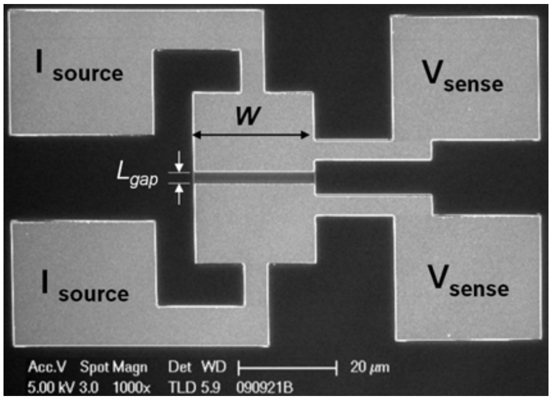

Fig 2: Scanning electron micrograph of the TLM pattern used for the contact resistivity (ρ_c) measurement. Separate pads were used for current biasing and voltage measurement.

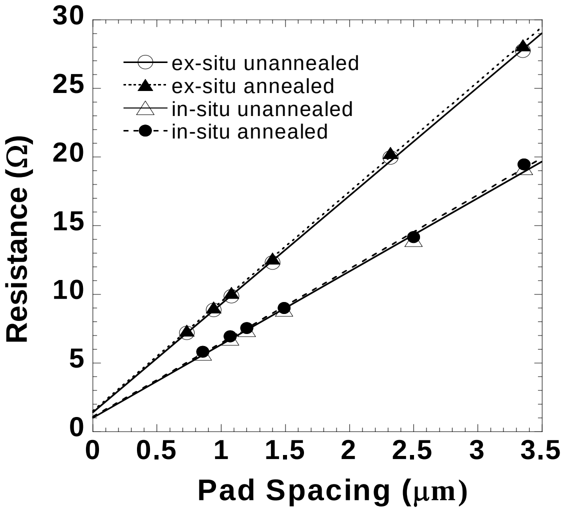

Fig 3: Measured TLM resistance as a function of pad spacing for un-annealed and annealed *in-situ* and *ex-situ* Ir contacts on p-$In_{0.53}Ga_{0.47}As$.

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