Ex-situ Tungsten Refractory Ohmic Contacts to p-InGaAs

Evan Lobisser[*,1], Ashish Baraskar[1], Vibhor Jain[1], Brian J. Thibeault[1], Arthur C. Gossard[2], and Mark J. W. Rodwell[1]

Depts. of [1]ECE and [2]Materials, University of California, Santa Barbara, CA 93106, USA

Developing THz bandwidth transistors requires very low resistance metal-semiconductor contacts. For both bipolar transistors [1] and FETs [2], contact resistivities ρ_c must be reduced by a factor of four to double device bandwidths. For InP BJTs, emitter and base $\rho_c < 2.0 \times 10^{8}\ \Omega\cdot\text{cm}^2$ are required to achieve simultaneous f_τ and f_{max} in excess of 1 THz. For multi-THz performance, contacts must maintain low resistivity while supplying current densities $J \sim 100\ \text{mA}/\mu\text{m}^2$, and resist diffusion due to thermal stress or high current through narrow layers ~10 nm thick [1]. We show here *ex-situ*, evaporated tungsten contacts to p-type $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ with $\rho_c = 5.5\ (+/-\ 6.9/4.1) \times 10^{-9}\ \Omega\cdot\text{cm}^2$, the lowest reported *ex-situ* p-type InGaAs contacts to date, with performance equivalent to the lowest resistivity p-type contacts formed *in-situ* [3].

The semiconductor epitaxial layers were grown by solid-source MBE on semi-insulating InP substrates [3]. Contact resistivities were measured on samples with five different hole concentrations varying in $\sim 5 \times 10^{19}\ \text{cm}^{-3}$ increments from $1.2 \times 10^{19}\ \text{cm}^{-3}$ to $2.2 \times 10^{20}\ \text{cm}^{-3}$. Active carriers, mobility, and sheet resistance of the samples was verified with Hall measurements, post-growth. Sample surfaces were prepared via 10 m UV-ozone oxidation, followed by 10 s 1:10 HCl:H_2O and 10 s de-ionized H_2O rinse immediately prior to loading samples in an e-beam evaporator. Tungsten 20 nm thick was blanket evaporated on the samples. After W deposition, transmission line model structures were formed, and resistance measurements carried out, using previously described processes and procedures [4].

Resistance measurements were taken both before and after samples were annealed in an N_2 environment at 250 °C for 60 m. Uncertainties in the extracted contact resistivities and sheet resistances were calculated by first evaluating individual uncertainties in each measured resistance and gap width, and then computing the difference in slope and intercept between a worst-case linear fit based on the individual uncertainties and a least-squares fit to the measured data. For un-annealed samples, $\rho_c = 5.5\ (+/-\ 6.9/4.1) \times 10^{-9}\ \Omega\cdot\text{cm}^2$, was measured on a sample with hole concentration, mobility, and sheet resistance of $p = 1.6 \times 10^{20}\ \text{cm}^{-3}$, $\mu = 22.5\ \text{cm}^2/\text{V}\cdot\text{s}$, and $R_{sh} = 174\ \Omega/\square$, the lowest reported *ex-situ* p-InGaAs contacts to date. Samples with $p = 2.2 \times 10^{20}\ \text{cm}^{-3}$, $1.1 \times 10^{20}\ \text{cm}^{-3}$, $5.0 \times 10^{19}\ \text{cm}^{-3}$, and $1.2 \times 10^{19}\ \text{cm}^{-3}$ demonstrated ρ_c of $1.39\ (+/-\ 0.90/0.66) \times 10^{-8}\ \Omega\cdot\text{cm}^2$, $3.95\ (+/-\ 1.77/1.41) \times 10^{-8}\ \Omega\cdot\text{cm}^2$, $2.24\ (+/-\ 0.45/0.40) \times 10^{-7}\ \Omega\cdot\text{cm}^2$, and $4.58\ (+/-\ 0.21/0.20) \times 10^{-5}\ \Omega\cdot\text{cm}^2$, respectively.

Annealed ρ_c increased from $5.5\ (+/-\ 6.9/4.1) \times 10^{-9}\ \Omega\cdot\text{cm}^2$ to $1.90\ (+/-\ 1.19/0.88) \times 10^{-9}\ \Omega\cdot\text{cm}^2$. We speculate the increase in resistivity associated with annealing may be due to migration of Ti through W having a columnar structure. Nevertheless, evaporated W is a good candidate for highly doped base contacts, especially in processes where *in-situ* techniques may be difficult to implement.

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*Corresp. author: lobisser@ece.ucsb.edu, Phone: +1-805-893-3273, Fax: +1-805-893-3262

Figures

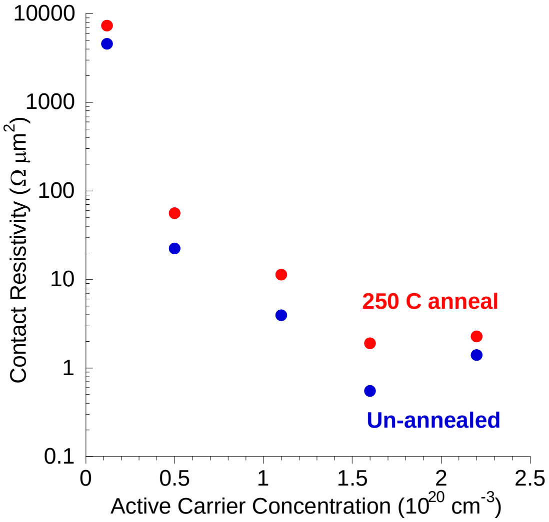

Fig. 1. Contact resistivity vs. carrier concentration for evaporated W contacts, before and after anneal

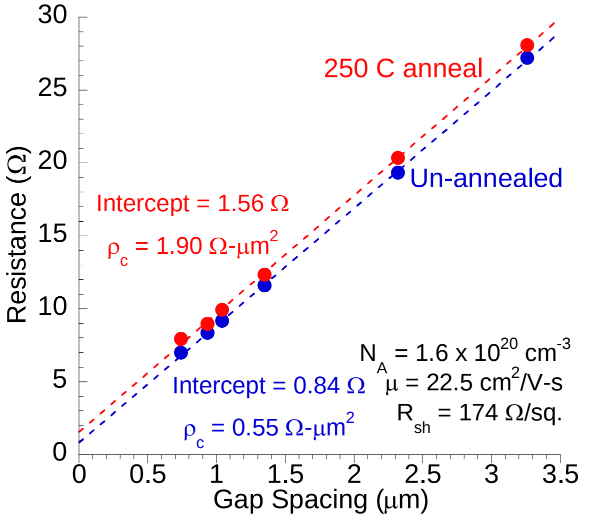

Fig. 2. Measured TLM resistance vs. gap spacing for both un-annealed and annealed W contacts

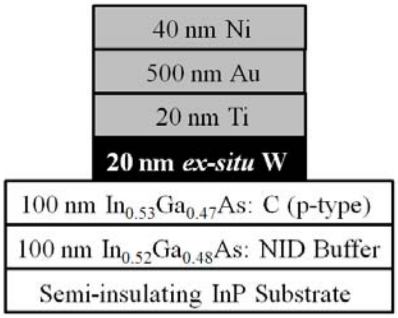

Fig. 3. Cross-sectional TLM layer structure. W was blanket evaporated separately from lifted off Ti/Au/Ni

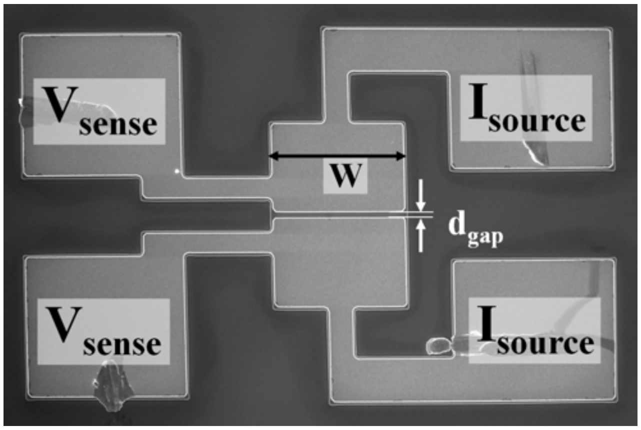

Fig. 4. Four-point pad structure used to extract ρ_c from TLM measurements, with gap spacing d and contact width W

p (10^{20} cm^{-3})	μ (cm^2/V·s)	R_{sh} (Ω/□)	ρ_c (10^{-8} Ω·cm^2) **Un-annealed**	ρ_c (10^{-8} Ω·cm^2) **250 °C anneal**
0.12	66.0	806.7	4579 (+/- 211/202)	7344 (+/- 309/294)
0.50	52.1	239.6	22.4 (+/- 4.51/4.00)	56.0 (+/- 7.54/6.88)
1.1	43.0	129.0	3.95 (+/- 1.77/1.41)	11.3 (+/- 3.04/2.61)
1.6	*22.5*	*174.0*	*0.55 (+/- 0.69/0.41)*	*1.90 (+/- 1.19/0.88)*
2.2	31.5	88.6	1.39 (+/- 0.90/0.66)	2.27 (+/- 1.14/0.88)

Fig. 5. Extracted contact resistivities for evaporated *ex-situ* W p-type $In_{0.53}Ga_{0.47}As$ contacts.