Title: Co–Doping of $In_xGa_{1-x}As$ with Silicon and Tellurium for Ultra-Low Contact Resistance

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The high dopant concentrations achievable by MBE provide a method for creating low-resistance ohmic contacts: increased doping decreases the depletion depth and increases tunneling.[1] Co-doping of the InAs (and thus $In_xGa_{1-x}As$) system with a group IV (Sn) and a group VI (Te) is possible and can provide high doping densities (2.9×10^{19} cm^{-3}).[2] As the group IV element must sit on a group III site to be a donor and the group VI element sits on the group V site, there is limited competition between the group IV and VI for a specific lattice site, which should allow for increased active electrical carriers. Additionally, Te has a lower diffusivity than Si (in GaAs), which will prevent unwanted movement of dopant atoms during thermal cycling.[3] We show that Te can dope $In_{0.53}Ga_{0.47}As$ up to 2.6×10^{19} cm^{-3}, and that the contact resistivity between an ex-situ deposited metal and Si and Te co-doped InAs and $In_{0.53}Ga_{0.47}As$ is lower than that of InAs and $In_{0.53}Ga_{0.47}As$ doped only by Si.

Samples were grown by solid source MBE lattice matched to semi-insulating InP with layer structure as follows from the substrate. Hall samples: 150 nm $In_{0.52}Al_{0.48}As$, 500 nm Te doped $In_{0.53}Ga_{0.47}As$ with Te (GaTe source material) cell temperatures of 475, 487, 500, 520, 525, 550, 562, 582, and 625 °C. Sample A: 400 nm $In_{0.52}Al_{0.48}As$, 3 nm of Si-doped 1×10^{19} cm^{-3} $In_{0.52}Al_{0.48}As$, 7 nm of $In_{0.53}Ga_{0.47}As$, 60 nm (Si or Si and Te doped) $In_{0.53}Ga_{0.47}As$. Sample B: 400 nm $In_{0.52}Al_{0.48}As$, 3 nm of Si-doped 2×10^{19} cm^{-3} $In_{0.52}Al_{0.48}As$, 10 nm of $In_{0.53}Ga_{0.47}As$, and 60 nm (Si or Si and Te doped) InAs. Samples A and B were removed from vacuum prior to growth of the top n^+ layer. To clean the surface prior to reloading to vacuum samples were oxidized with UV ozone and those oxides were removed by a 1 min. dip in 10 H_2O:1 HCL. Samples were heated to 420 °C and treated with thermally cracked hydrogen ($\approx 1\times10^{-6}$ Torr) for 40 minutes prior to regrowth. After regrowth Samples A and B were metalized with lifted-off e-beam evaporated Ti/Pd/Au and mesa isolated. Contact resistances were extracted by transmission line measurements (TLM).

Room temperature Hall measurement of the Te doped $In_{0.53}Ga_{0.47}As$ Hall samples using standard Van der Pauw technique showed electrically active carrier concentrations of up to 2.6×10^{19} cm^{-3} (with mobility of 1466 cm^2/Vs) without saturation effects. The contact resistivity to the Si and Te co–doped InAs (sheet resistance of 18.9 Ω) was 6.6 Ω–μm (2.3 $\Omega\text{–}\mu m^2$) while the contact resistivity to the Si doped InAs (sheet resistance of 25.3 Ω) was 9.9 Ω–μm (3.9 $\Omega\text{–}\mu m^2$). The contact resistivity to the Si and Te co-doped $In_{0.53}Ga_{0.47}As$ (sheet resistance of 24 Ω) was 6.8 Ω–μm (1.9 $\Omega\text{–}\mu m^2$) while the contact resistivity to the Si doped $In_{0.53}Ga_{0.47}As$ (sheet resistance of 31 Ω) was 8.5 Ω–μm (2.3 $\Omega\text{–}\mu m^2$). These results suggest that co-doping of $In_xGa_{1-x}GaA$ by Si and Te is an effective way to lower the metal-semiconductor contact resistance and resistivity. Hall and AFM measurements of co-doped are forthcoming.

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[1] A. K. Baraskar *et al.*, JVST B **27**, 2036 (2009).
[2] H. G. Lee *et al.*, J. Cryst. Growth **130**, 416 (1993).
[3] R. Sankaran, J. Cryst. Growth **50**, 859 (1980).

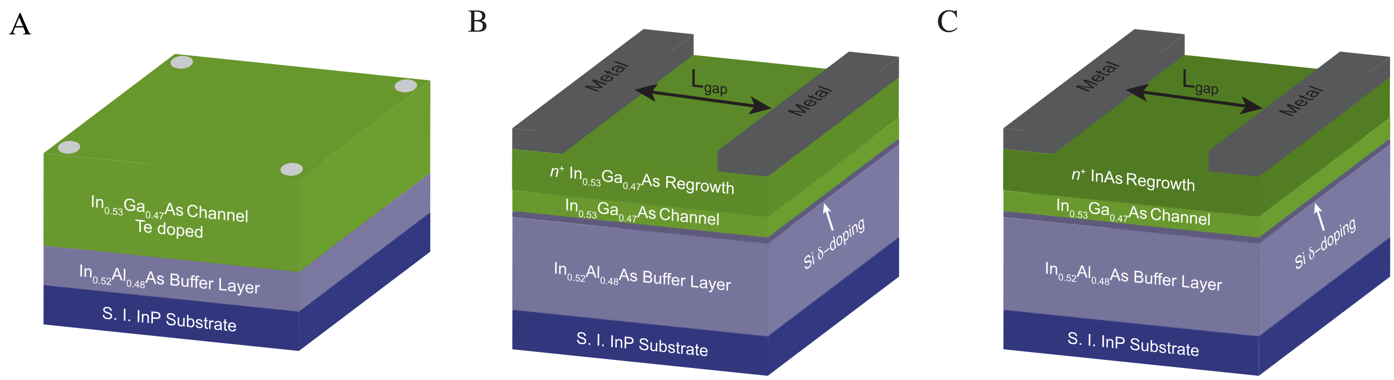

Fig. 1: Schematic illustration of the sample structures (a) Hall sample (b) Sample B (v7 nm channel with $In_{0.53}Ga_{0.47}As$ regrowth) and (c) Sample C (10 nm channel with InAs regrowth)

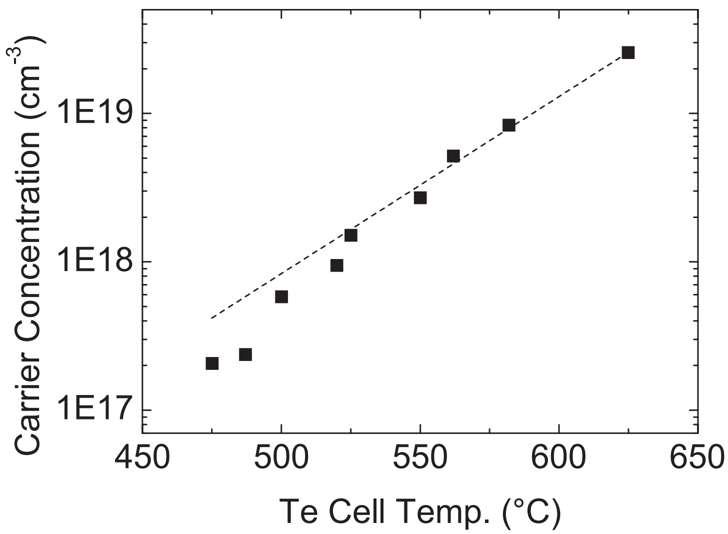

Fig. 2: Plot of Te cell temperature versus measured free electron concentration as measured by Hall.

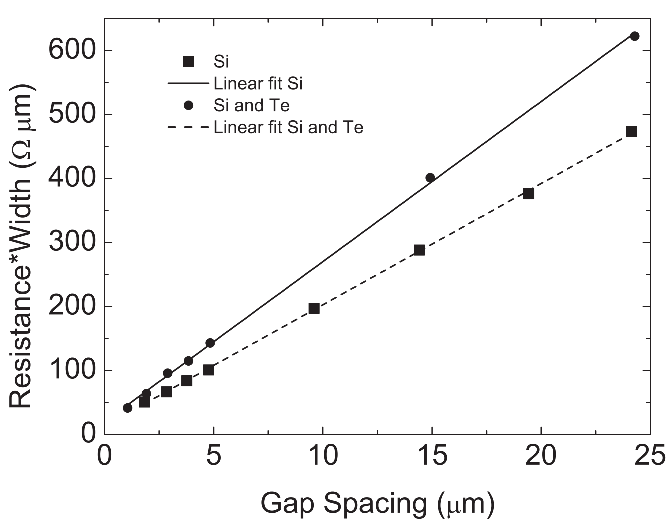

Fig. 3: Plots of measured resistance versus gap spacing for Si-doped InAs regrowth (circles) and Si- and Te- doped InAs regrowth (squares) with linear fits as solid and dashed line, respectively.

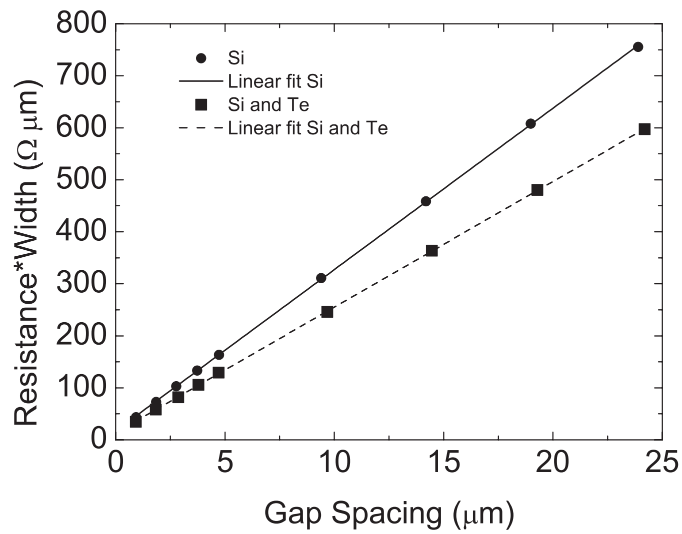

Fig. 4: Plots of measured resistance versus gap spacing for Si-doped InGaAs regrowth (circles) and Si- and Te- doped InGaAs regrowth (squares) with linear fits as solid and dashed line, respectively.