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

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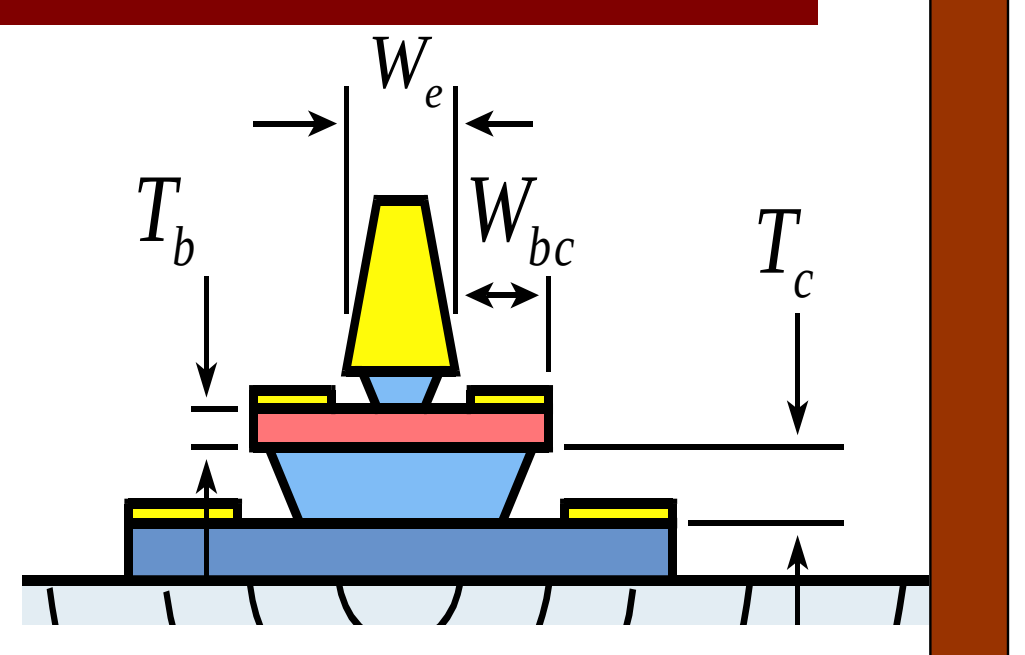
INTRODUCTION

GOAL: High Frequency Electronics

- THz electronics limited by metal-semiconductor contacts
- Need contact resistivity (ρ_c)< 2x10^{-8} Ω-cm^2 for f_t and f_{max} >1 THz [1]
- Usually involve high temperature processing; high current densities (~100 mA/μm^2)
- Unpredictable native oxides

Fundamental Scaling Laws



To double device bandwidth:

- Cut transit time 2x
- Cut RC delay 2x

Scale contact resistivities by 4:1*

$$f_{max} = \sqrt{\frac{f_\tau}{8\cdot\pi\cdot(R_{bb}\cdot C_{cb})_{eff}}}$$

$$\frac{1}{2\pi f_\tau} = \tau_{in} + RC$$

InP Bipolar Transistor Scaling Roadmap

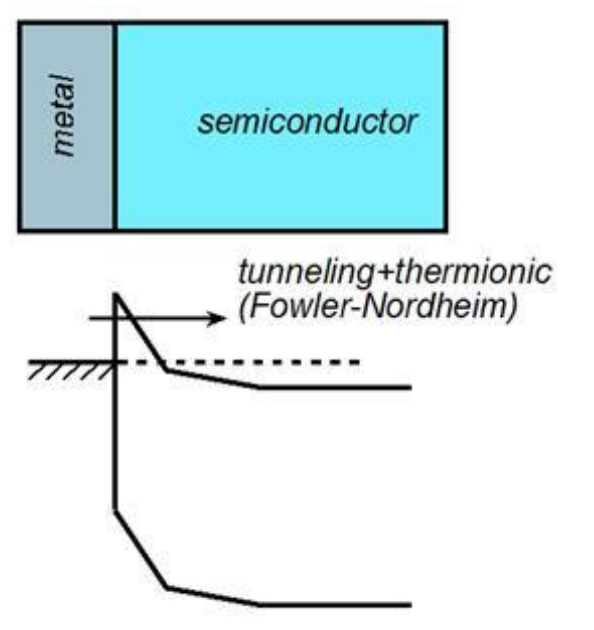
Emitter	256	128	64	32	nm, **width**
	8	**4**	**2**	**1**	Ω·μm^2, **access ρ**
Base	**175**	**120**	**60**	**30**	nm, **contact width**
	10	**5**	**2.5**	**1.25**	Ω·μm^2, **contact ρ**
f_t	**520**	**730**	**1000**	**1400**	GHz
f_{max}	**850**	**1300**	**2000**	**2800**	GHz

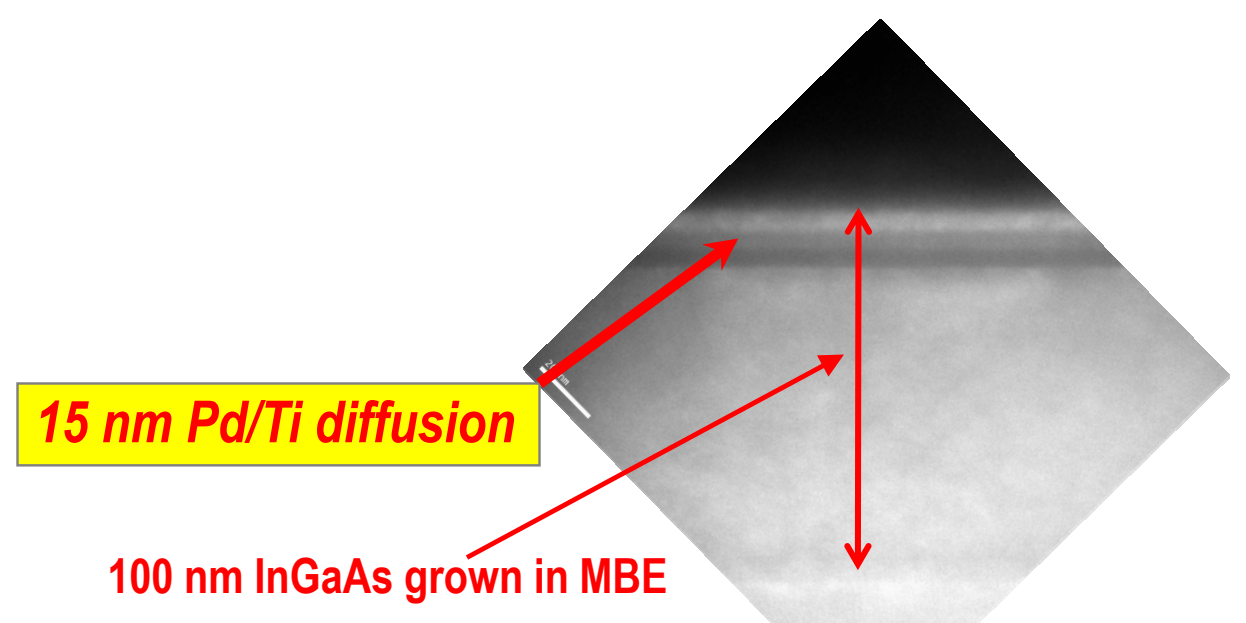
Less than 2 *Ω-μm^2* contact resistivity required for simultaneous THz f_t and f_{max} [2]

Approach

Requirements for achieving low resistance, stable ohmic contacts

- Higher number of active carriers
- Better surface preparation techniques
- Use of refractory metal for thermal stability





- Scaled device ⟶ thin base
  (For 80 nm device: t_{base} **< 25 nm)**
- Non-refractory contacts may diffuse at higher temperatures through base and short the collector
- Pd/Ti/Pd/Au contacts diffuse about 15 nm in InGaAs on annealing

Need a refractory metal for thermal stability

EXPERIMENTAL DETAILS

Epilayer Growth

Semiconductor epilayer growth by Solid Source Molecular Beam Epitaxy (SS-MBE)– p-InGaAs/InAlAs

- Semi insulating InP (100) substrate
- Unintentionally doped InAlAs buffer
- Hole concentration determined by Hall measurements

In-situ contacts

In-situ iridium (Ir) deposition immediately after film growth
-E-beam chamber connected to MBE chamber
-No air exposure after film growth

Ex-situ Contacts

- Surface exposed to air
- Oxidized with UV-ozone for 30 min
- Dilute HCl (1:10) etch and DI rinse for 1 min each
- Hydrogen cleaning at 70 °C for 30 min in MBE system
- Surface morphology verified by RHEED
- Ir deposition in the e-beam chamber connected to MBE chamber

Why Ir?

- Refractory metal (melting point ~ 2460 °C)
- Work function ~ 5.7 eV; closer to E_v for InGaAs
- Easy to deposit by e-beam technique

Atomic H Cleaning:

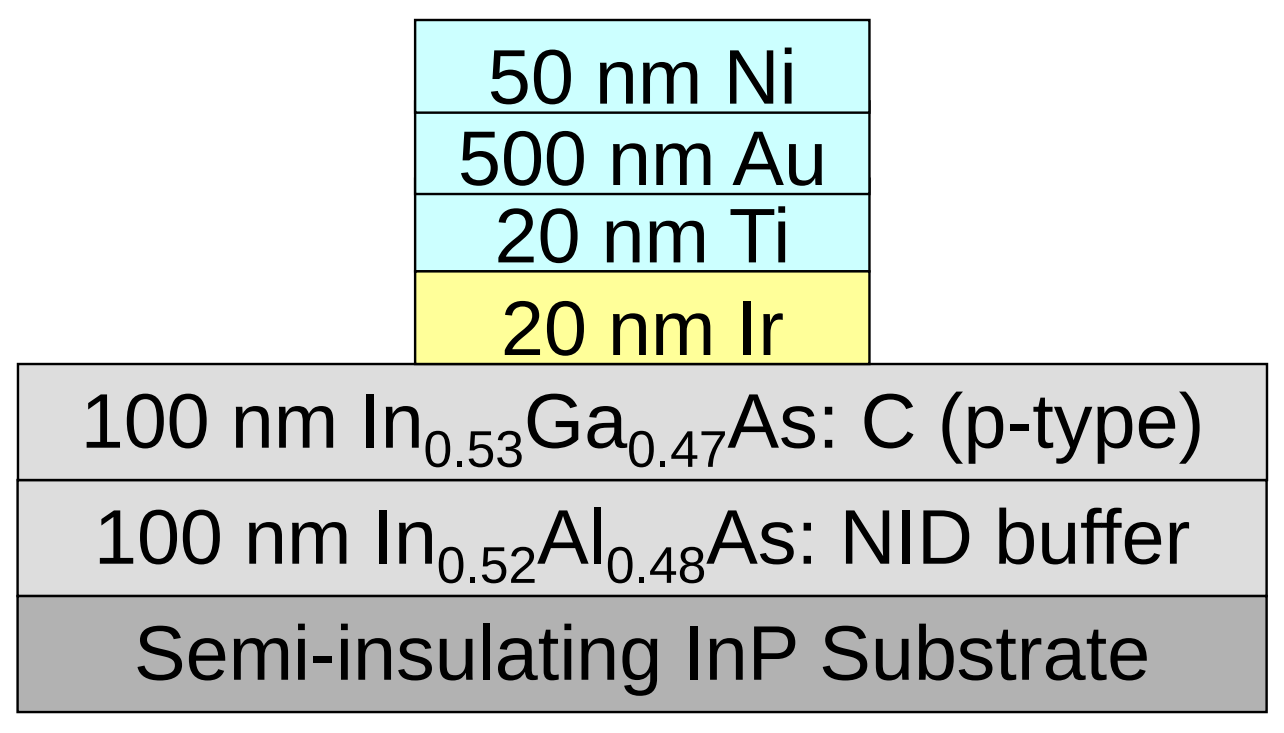
- Oxides and hydrocarbons form the majority of surface impurities
- Atomic H reacts with oxides to form volatile products [3]

$$As_2O_x + 2xH \longrightarrow xH_2O\uparrow + As_2\uparrow$$
$$In_2O_3/Ga_2O_3 + 4H \longrightarrow 2H_2O\uparrow + In_2O/Ga_2O\uparrow$$
$$In_2O_3/Ga_2O_3 + 4H \longrightarrow H_2O\uparrow + 2InOH/2GaOH\uparrow$$

- Similarly carbon containing complexes (InGaAs-C) are broken into volatile products

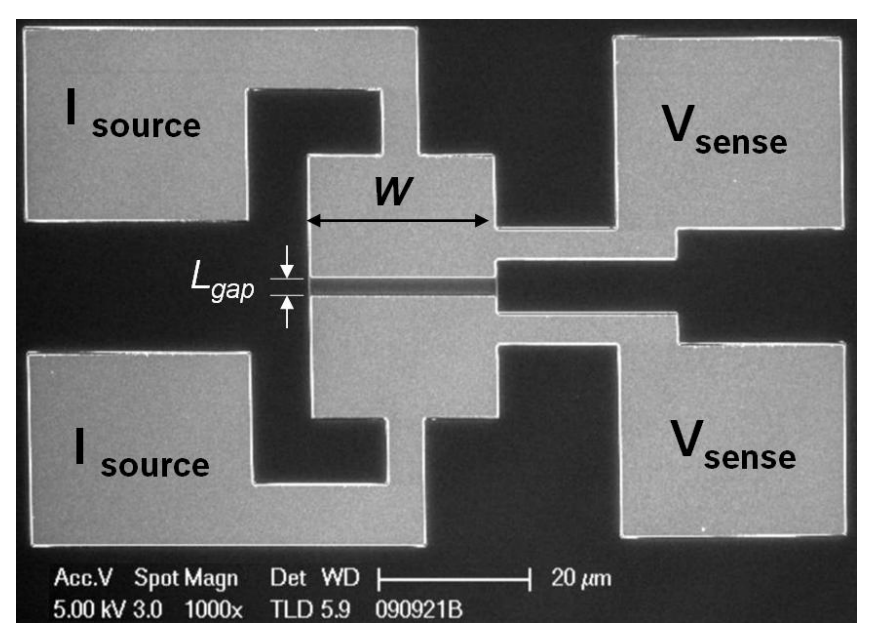
Characterization and Measurements

- TLM Fabrication by photolithography and liftoff
- Ir dry etched in SF_6/Ar with Ni as etch mask; InGaAs isolation by wet etch
- Separate probe pads from contacts to minimize parasitic metal resistance
- Gap Spacing: 0.5 – 25 µm (verified by SEM)
- Resistance measured by 4155C parameter analyzer



50 nm Ni
500 nm Au
20 nm Ti
20 nm Ir
100 nm $In_{0.53}Ga_{0.47}As$: C (p-type)
100 nm $In_{0.52}Al_{0.48}As$: NID buffer
Semi-insulating InP Substrate

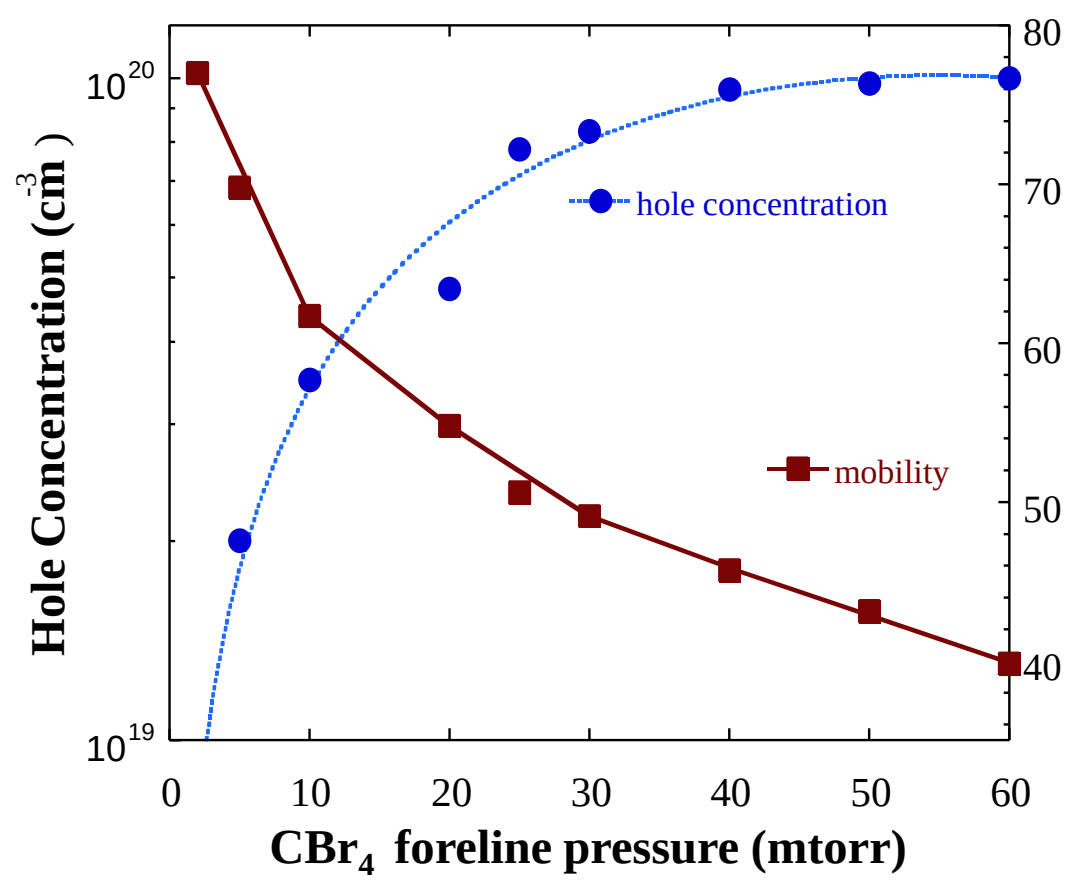
Cross-section schematic of the metal-semiconductor contact layer structure used for TLM measurements



Schematic of the TLM pattern used for the contact resistivity measurement

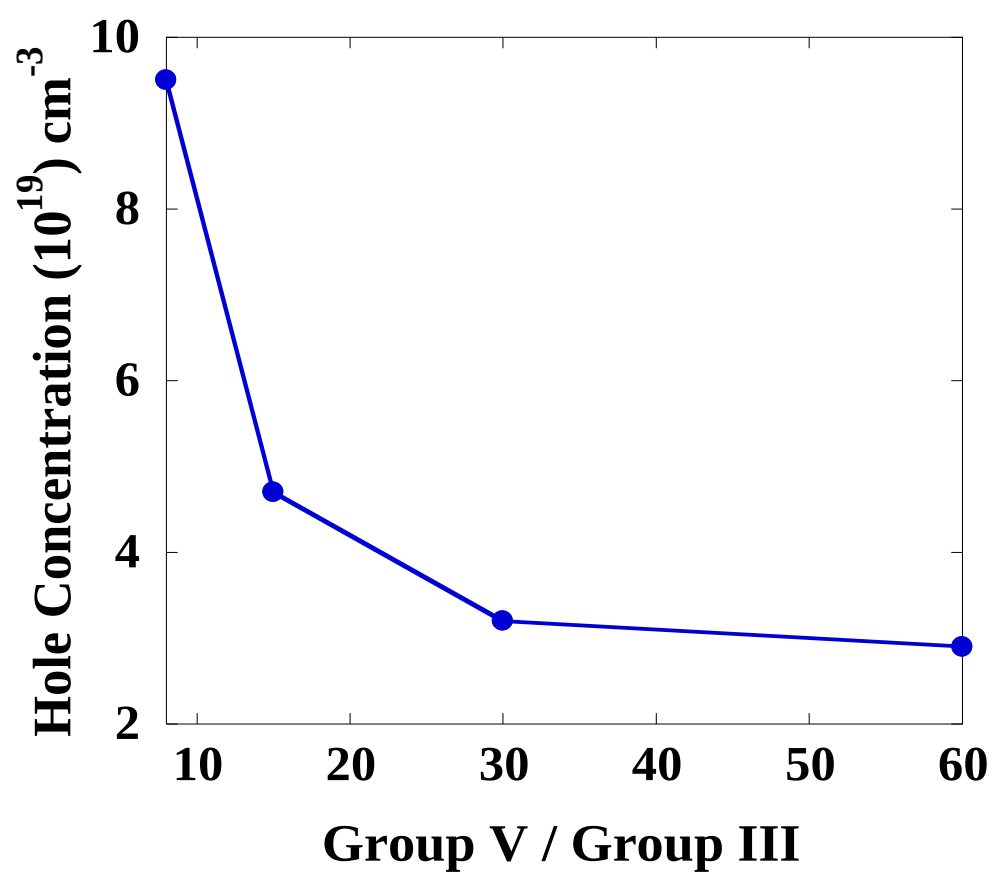
RESULTS

Hole concentration Vs CBr_4 flux



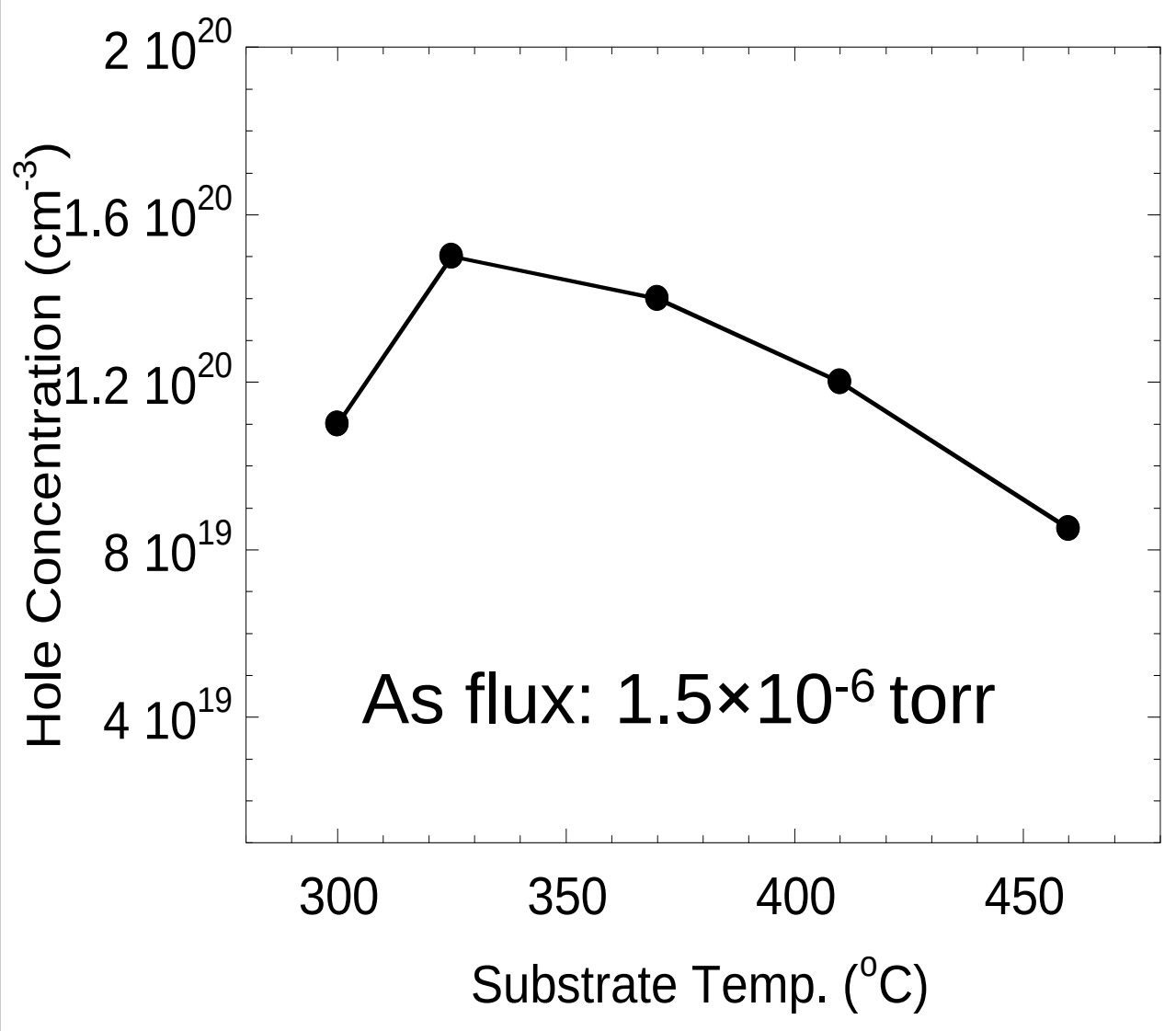
- Hole concentration saturates at high CBr_4 fluxes
- Number of di-carbon defects increases as CBr_4 flux increases[4]

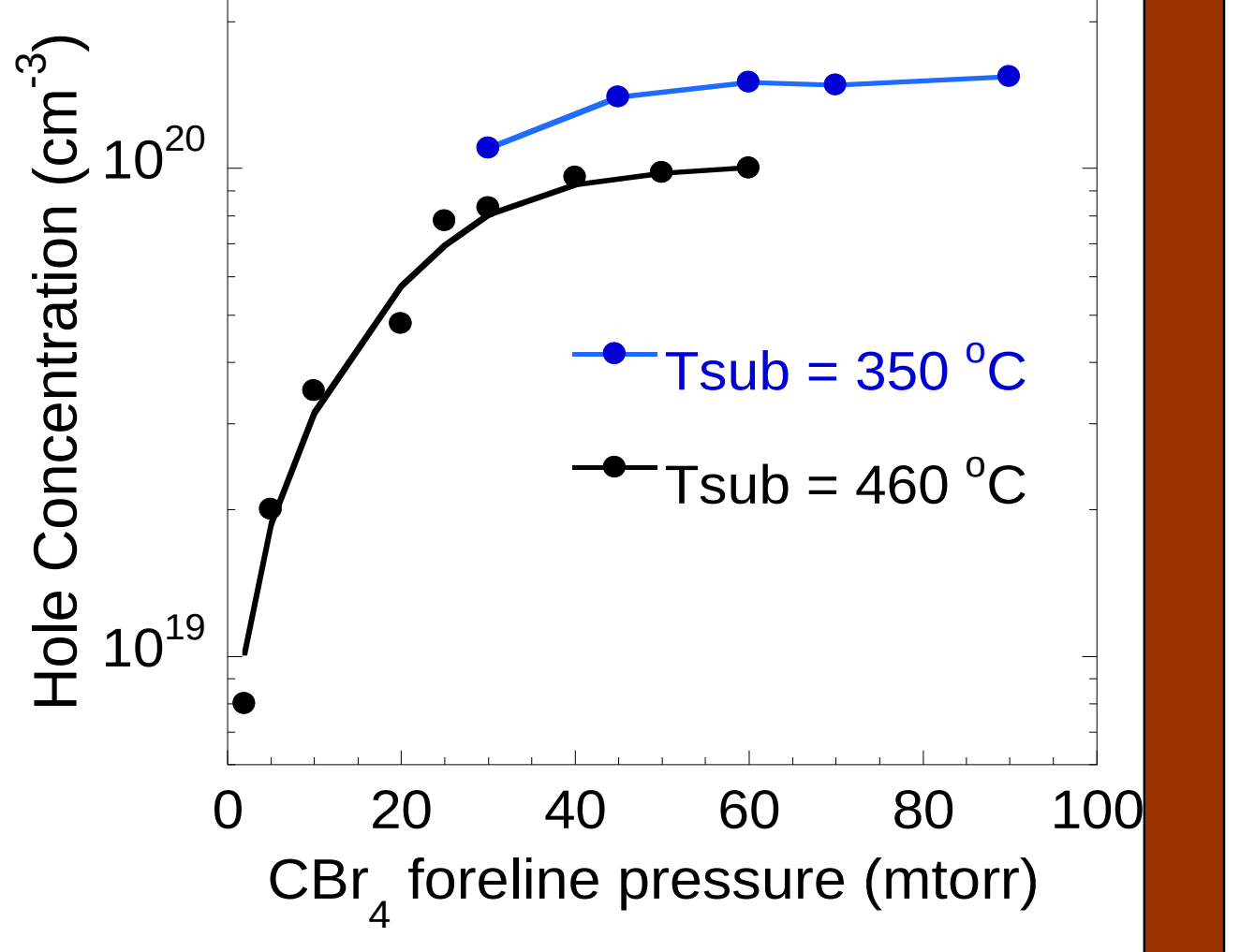
Hole concentration Vs V/III flux



- As V/III ratio decreases hole concentration increases
- hypothesis: As-deficient surface drives C onto group-V sites

Hole concentration Vs substrate temperature





Tendency to form di-carbon defects increases as T_{sub} increases[4]

Process	Surface Preparation	ρ_c (*Ω-µm^2*)	ρ_h (*Ω-µm*)
In-situ	As grown	**1.0±0.6**	11.5±3.3
Ex-situ (air exposure)	HCl etch + H clean (MBE)	**1.5 ± 0.9**	17.4 ± 4.2

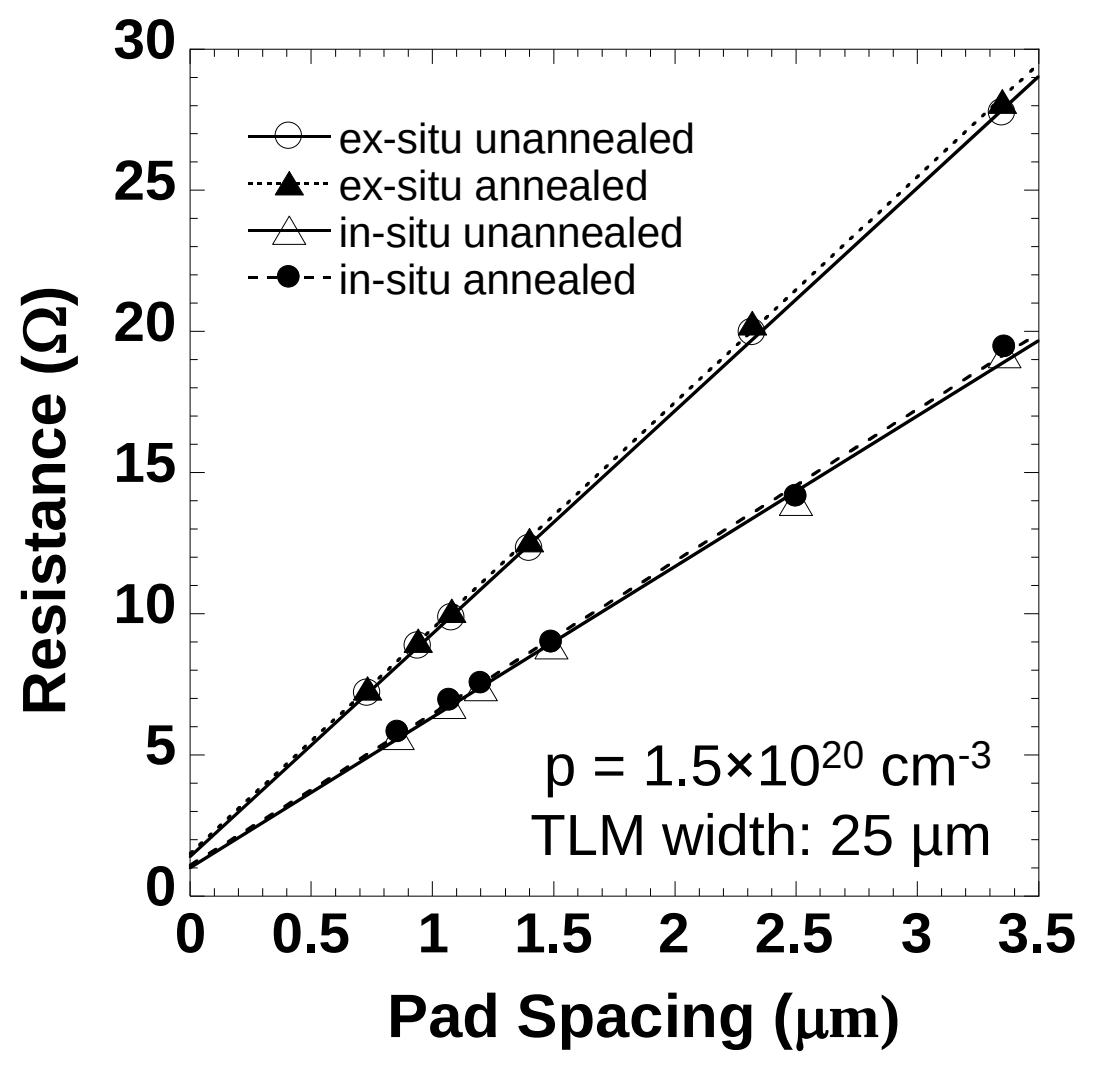
- **Hole concentration, p = 1.5 x 10^{20} cm^{-3}**
- **Mobility, µ = 36 cm^2/Vs**
- **Sheet resistance, R_{sh} = 105 ohm/▯ (100 nm thick film)**

ρ_c lower than the best reported contacts to p-InGaAs (ρ_c = 4 Ω-µm^2)[5,6]

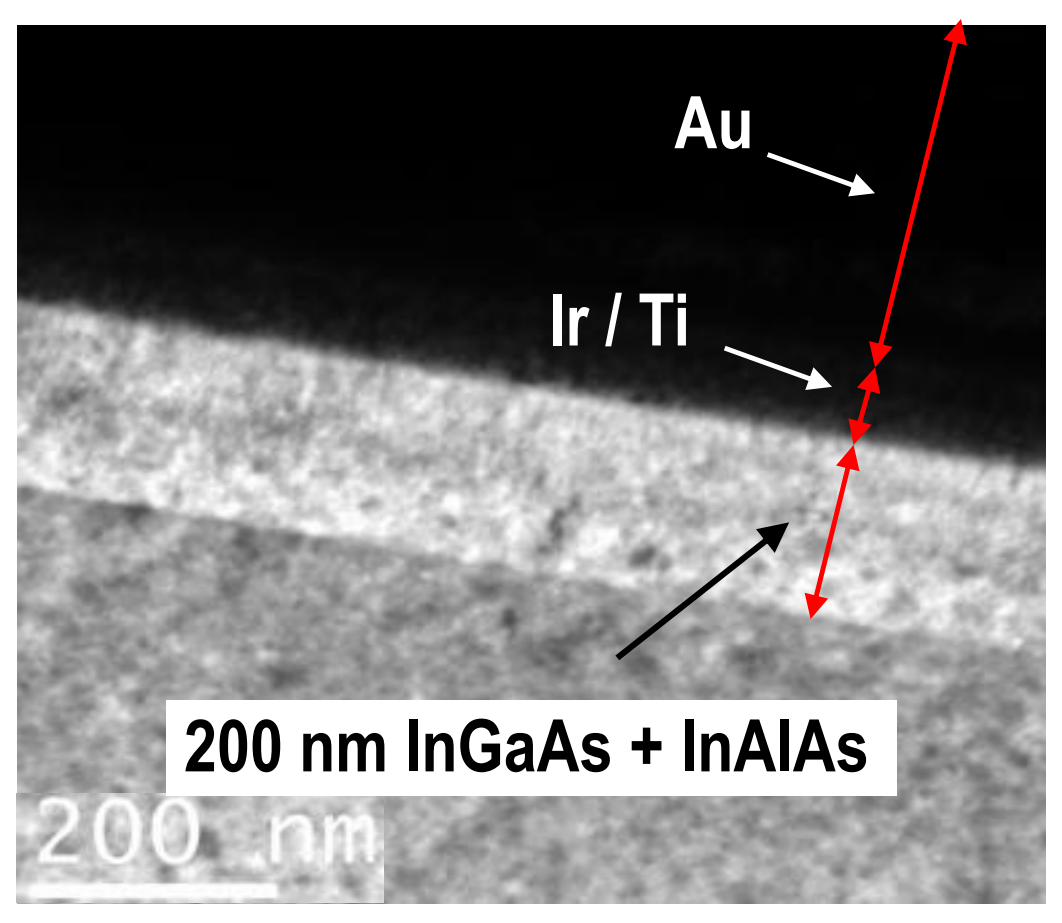
Thermal Stability:

- Contacts annealed under N_2 flow at 250 °C for 60 min.

Process	ρ_c (*Ω-µm^2*)	
	Un-annealed	**annealed**
In-situ	1.0±0.6	1.2±0.7
Ex-situ (air exposure)	1.5 ± 0.9	1.8 ± 0.9



TLM resistance as a function of pad spacing



TEM image of the Ir/p-InGaAs contact after annealing

Error Analysis

- Error due to extrapolation
  - Error in 4-point probe resistance measurements
  - Resolution error in SEM
- Error due to processing
  - Variable gap along width (W)
  - Overlap resistance

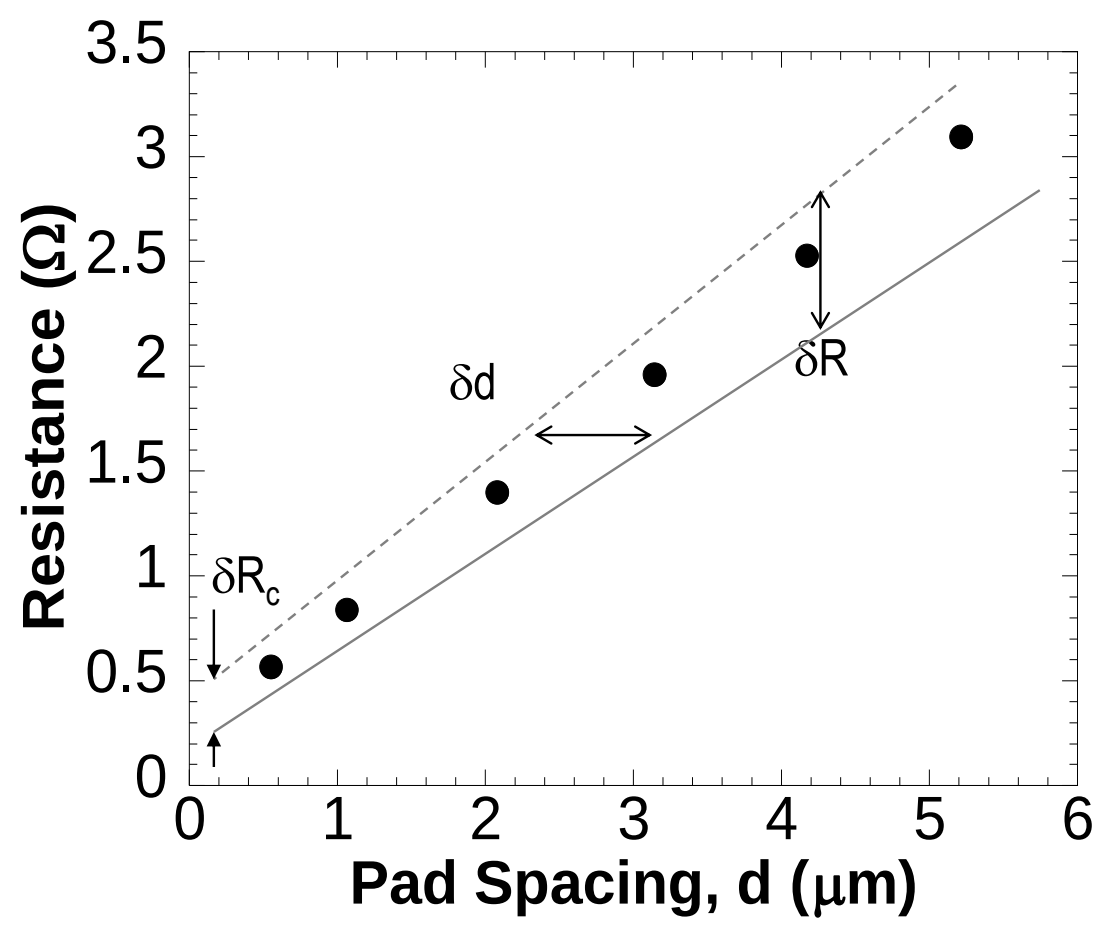
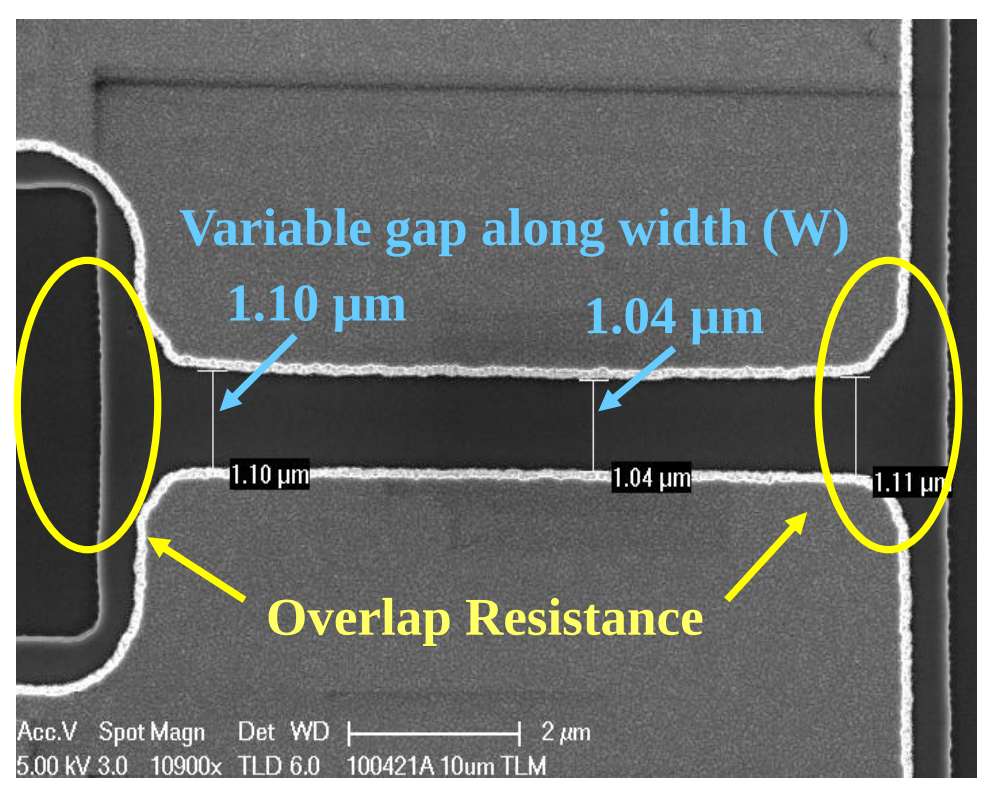


Illustration of systematic error, either by δR or by δd, on the plot of resistance R versus pad spacing d



SEM images of the TLM sample illustrating the errors due to processing

Conclusions

- Low contact resistivity with in-situ Ir contacts:
  ρ_c ~ (1.0 ± 0.6) Ω-µm^2
- ρ_c with ex-situ Ir contacts ((1.5 ± 0.9) Ω-µm^2) is comparable to that obtained with in-situ contacts.
- Slight degradation in ρ_c on annealing but contacts still suitable for THz transistors

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