Dublin City University
School of Electronic Engineering

Advances in semiconductor materials and device metrology

CIICT 2007
DCU, 28 Aug 2007.

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RINCE | Research Institute for Networks and Communications Engineering

sfi science foundation ireland

ENTERPRISE IRELAND

NCPST National Centre for Plasma Science & Technology

Co-Workers

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- Prof. Nick Cowern, University of Newcastle.
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Metrology Challenges

- Length scales
  - Lateral (X-Y)
  - Vertical (Z).

- Requirements:
  - Non-destructive.
  - *In situ*.
  - In line.
  - “Nano” sensitivities: small volumes, areas (nm-scale); impurity sensitivites (e.g. 10^{12} - 10^{13} cm^{-3}); nano-void and nano-pore detection; etc.

Low-k metrology challenges

- New low-k dielectrics have different mechanical/physical properties compared to SiO_2.
- Pores in the material.
- Fragile – delamination; stress-induced fracture.
- Back end of the line (BEOL): problems with assembly and packaging.
- No convenient and competent metrology tools.

***Source:* ITRS 2005**

Cu metallisation metrology challenges

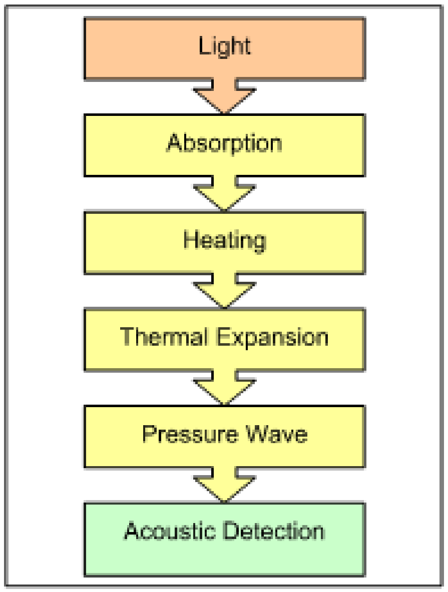
Source: ***ITRS 2005***

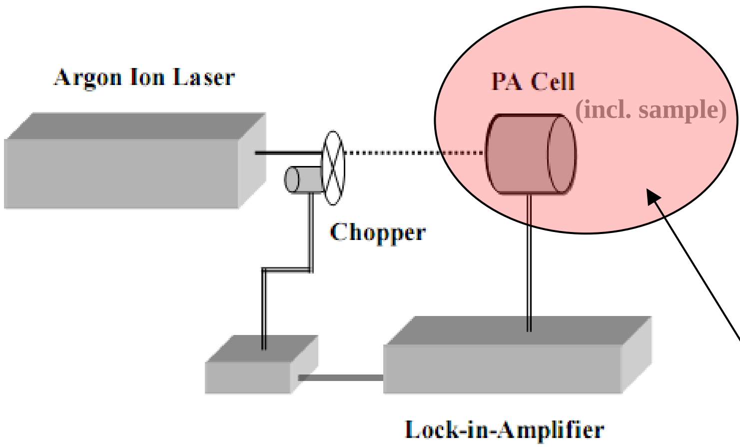
- Measuring barrier layer(s) under seed copper.
- Detection of voids in copper lines after CMP and anneal processes.
- Thick Cu lines mask this voiding.
- Detection through multi-layer structures e.g. individual layer thicknesses.
- Delamination of Cu from e.g. low-k layers before and after CMP.
- Local stress vs. wafer stress.
- Adhesion strength measurements are still done using destructive methods.
- Detection of killer pores and voids is not yet possible.

A Selection of DCU's metrology approaches

- Gas Cell Photoacoustic Microscopy
- Micro-Raman Spectroscopy

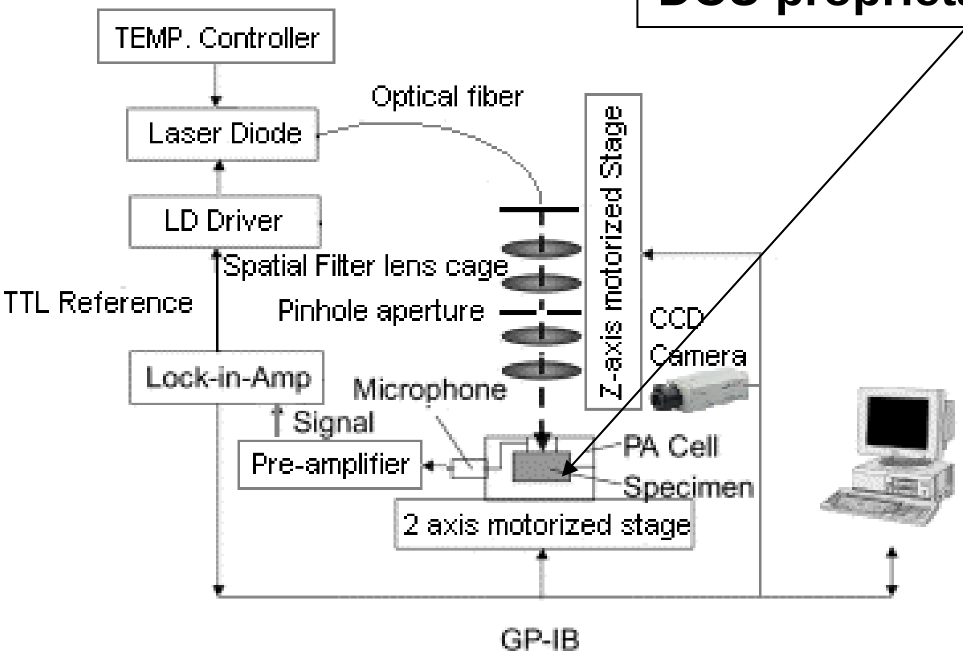
Photoacoustic Microscopy (PAM)



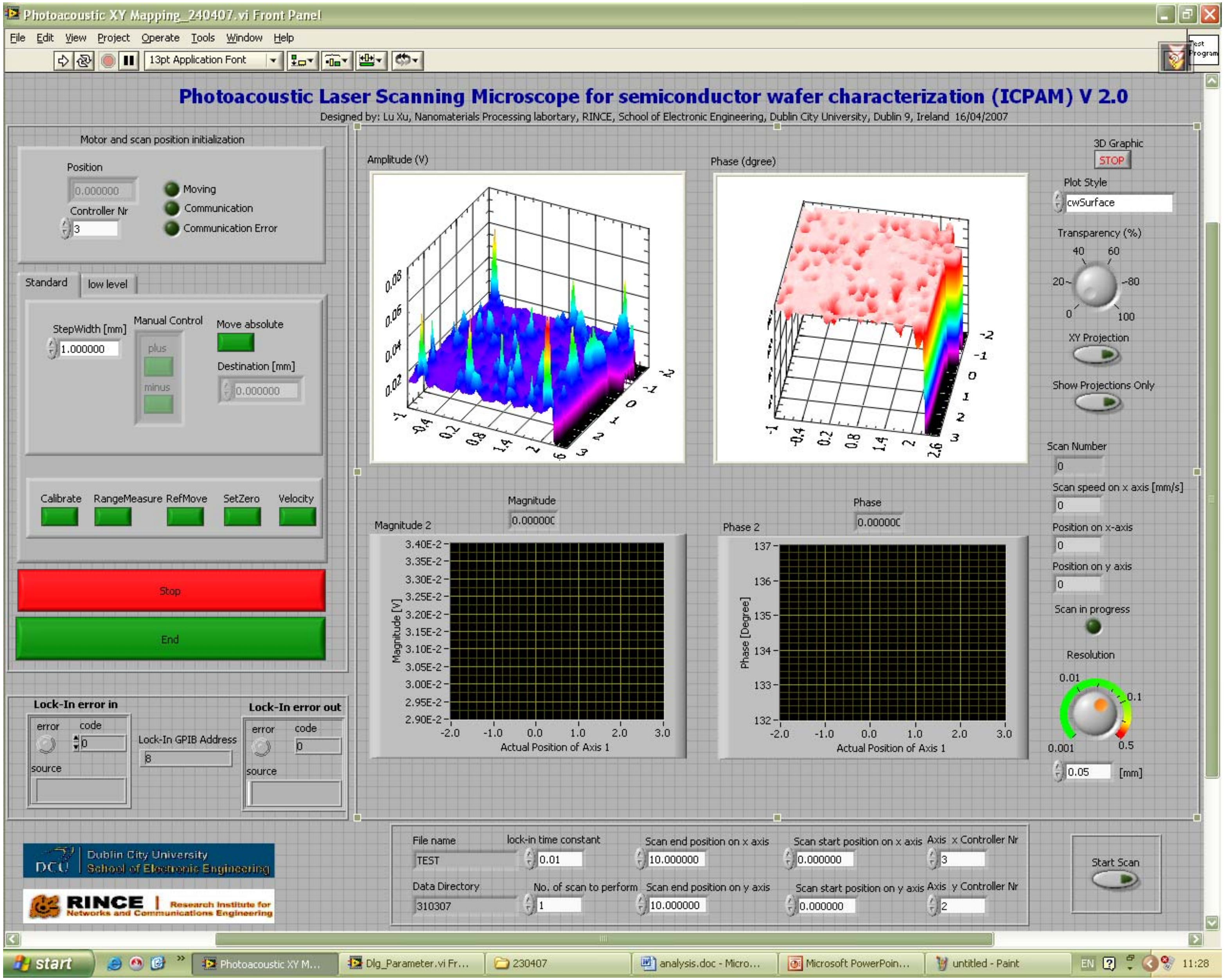


Source: ***N. George, Cochin Univ. Sci. & Tech., India.***

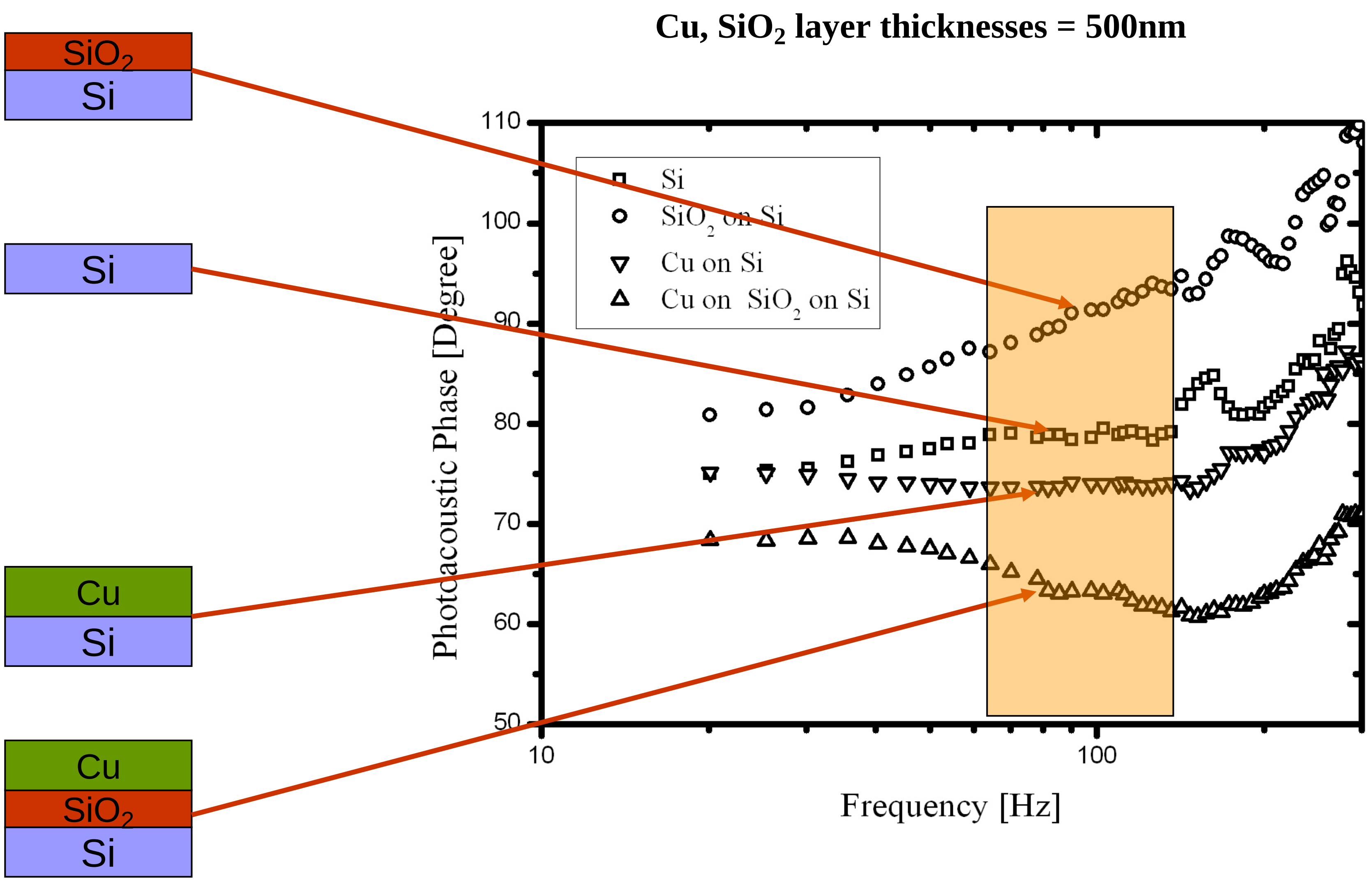
DCU proprietary PA cells



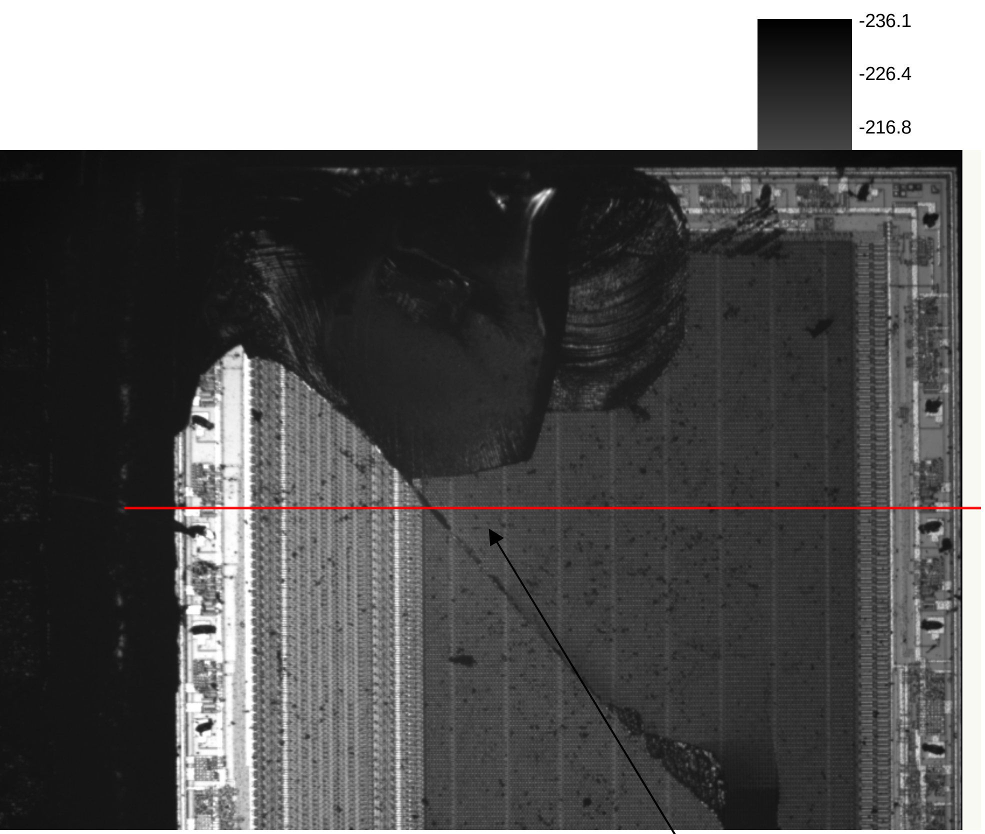
Automated PAM system for Si wafer analysis



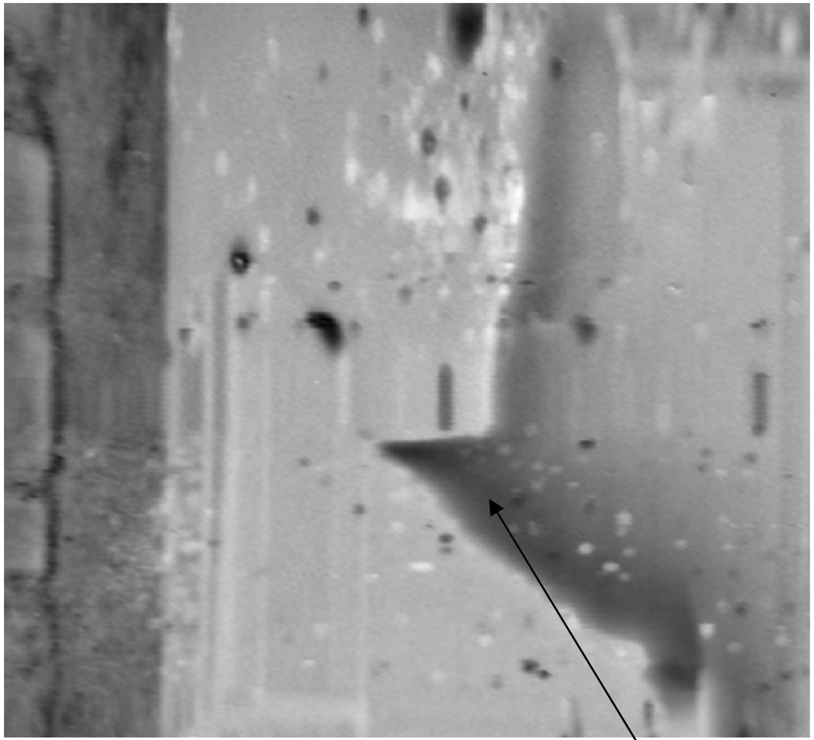
Analysis of multi-layer structures on Si wafers



IC Chip Cracking & Delamination



Optical Micrograph

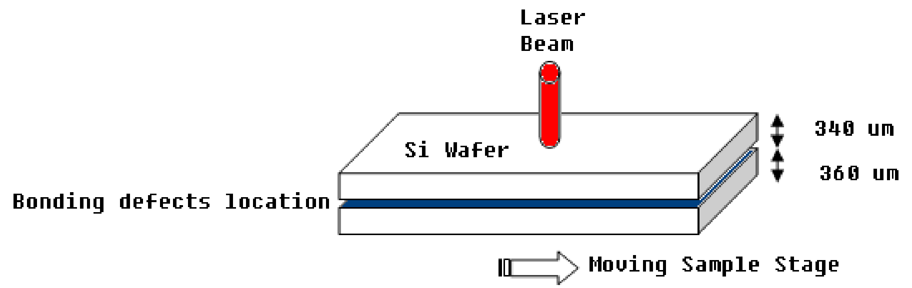


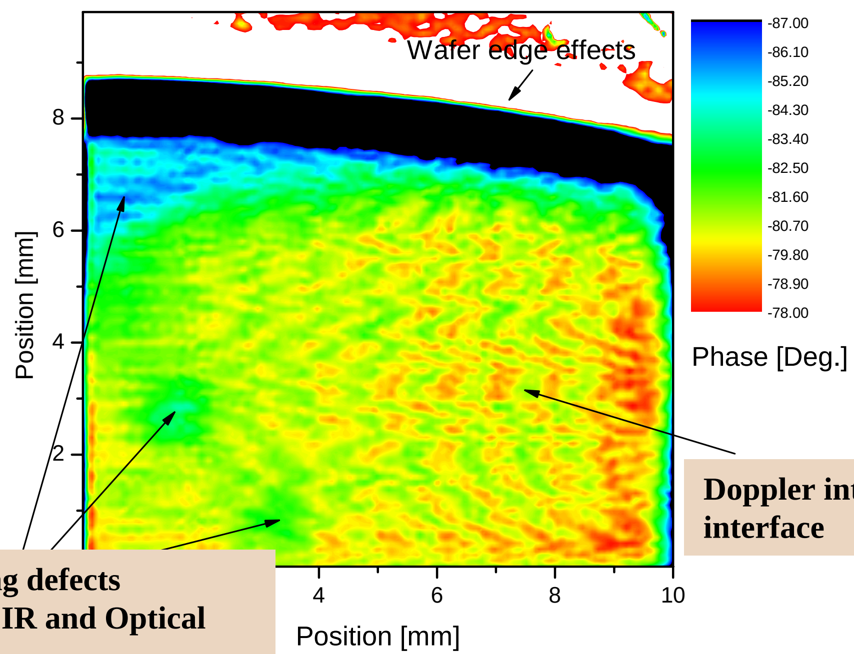
Delamination

Photoacoustic Phase Image

Wafer bonding defects (Phase Contrast)

L. Xu, P McNally, *DRIP XII*, 9 - 13 September 2007 Berlin (Germany).





ICPAM Phase image (f =216 Hz).

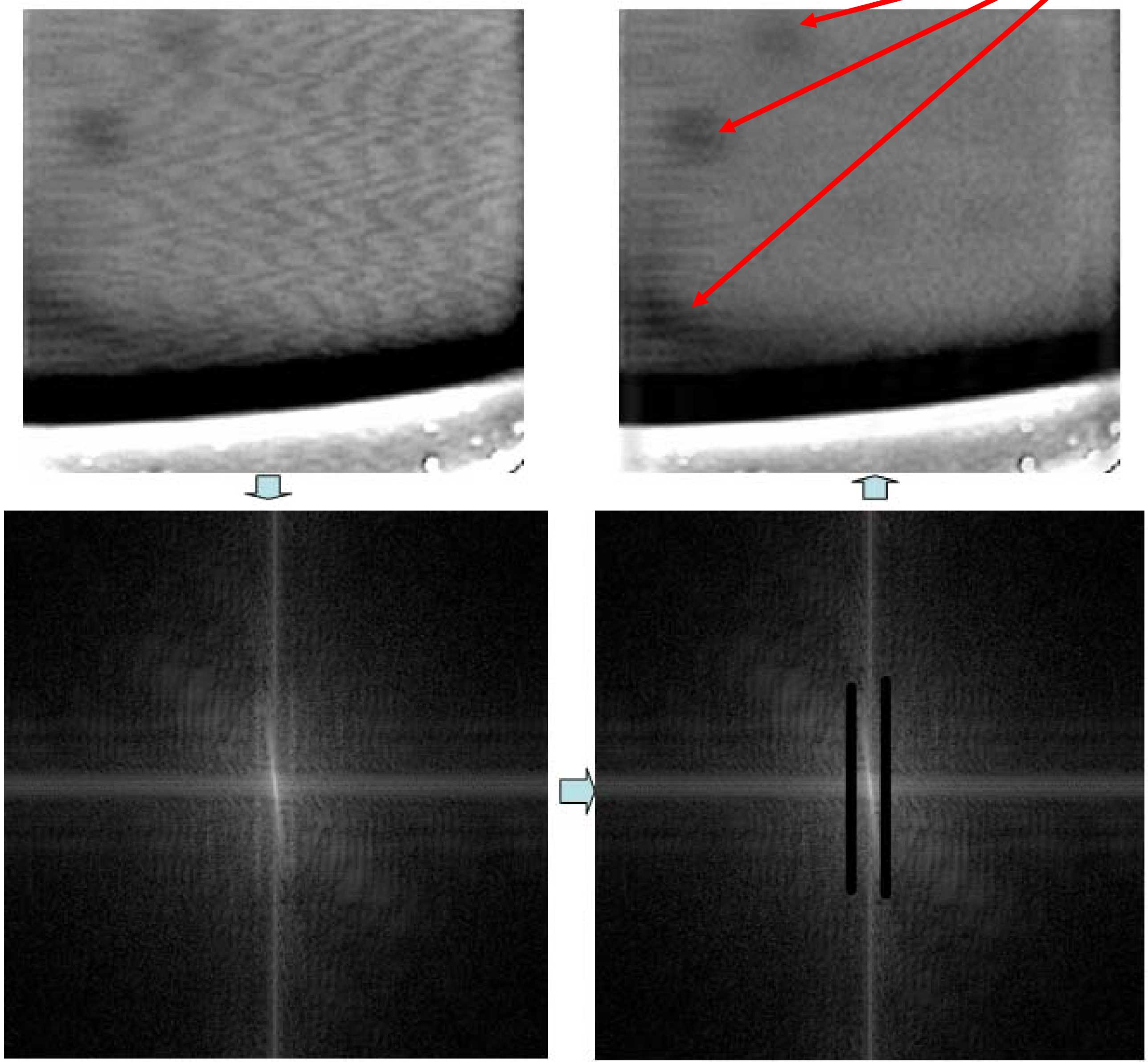
- 10,000 pixel image shown is obtained in 8 minutes.
- The bonding defects acted as extra thermal barrier, shown as extra time delay in phase images.

Doppler interference effect at bonded interface

Wafer bonding defects confirmed by IR and Optical Microscopy

After Image Processing

DELAMINATION



Remove the interference fringe using 2D FT methods

Software: ImageJ

Ongoing PAM Developments

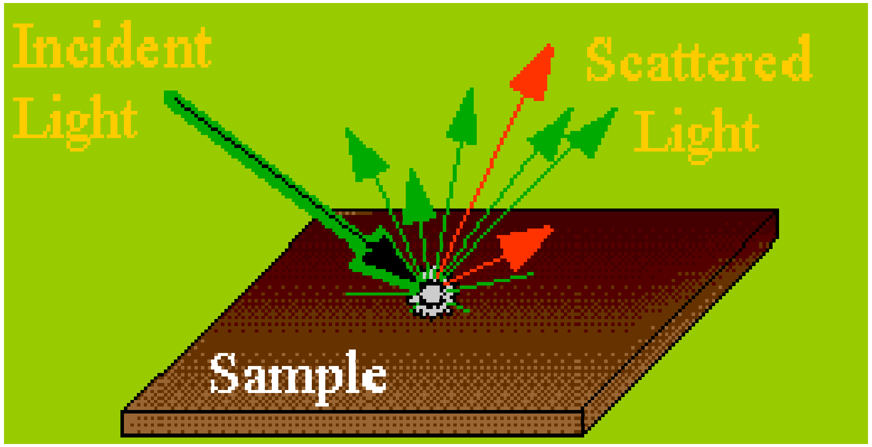
- Upgrade to 200 mm & 300 mm wafer capability (end-2007 – Enterprise Ireland Proof of Concept Fund)
- Porous dielectric measurements – early results promising.
- Wafer edge sub-surface cracks.
- Measure nm-scale delamination.
- Technology licensing underway.

Summary for Photoacoustic Microscopy

- Can see through opaque (metallic) layers.
- Multi-layer characterisation : thicknesses, delamination, porosity.
- Nanometric vertical scale sensitivities.
- Whole wafer scanning.

Micro-Raman Spectroscopy (μRS)

- Incident light excites vibrational modes in the sample. Subsequently scatter the light.
- Some light is scattered at a different energy (wavelength).
- Energy exchange between incident photons and semiconductor phonons (internal vibrational modes).
- Raman light intensity is very weak.
- Typically about one photon out of 10^{12}.
- $E_{phonon} = E_{incident} - E_{scattered}$

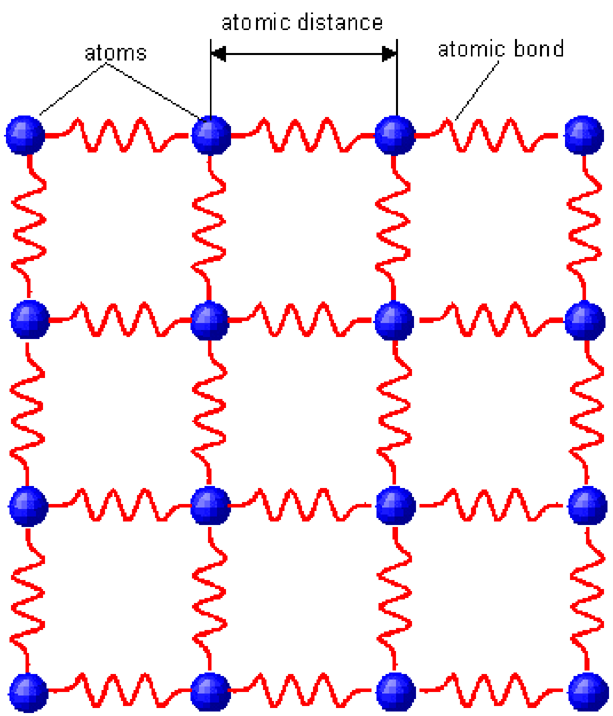


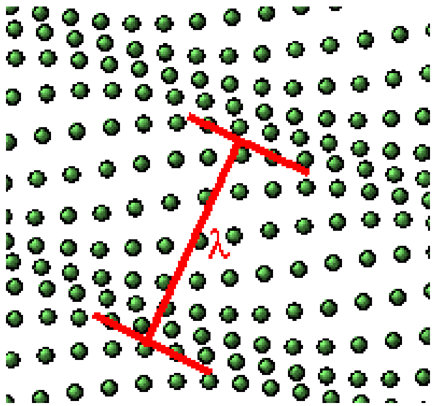
•Probe regions ~ 1μm diam.

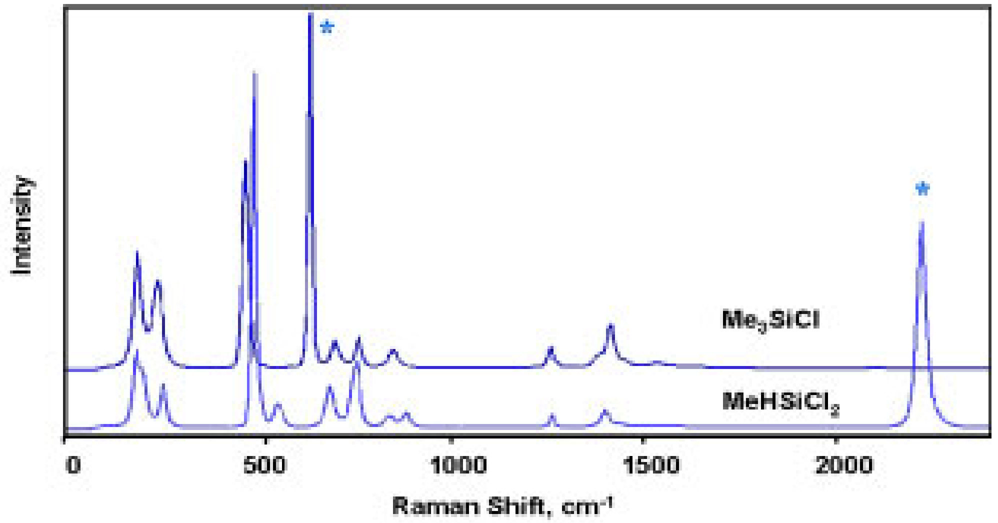
•325nm laser → Si penetration depth ~ 9nm →

•True nanometric scale depth metrology.

- Strained/deformed crystal.
- Vibrations of crystal lattice altered.
- “Spring constant(s)” between atoms changed.
- Shifts frequency of inelastically scattered Raman photons.
- A plot this shifted light ouput intensity vs. frequency is a Raman spectrum.

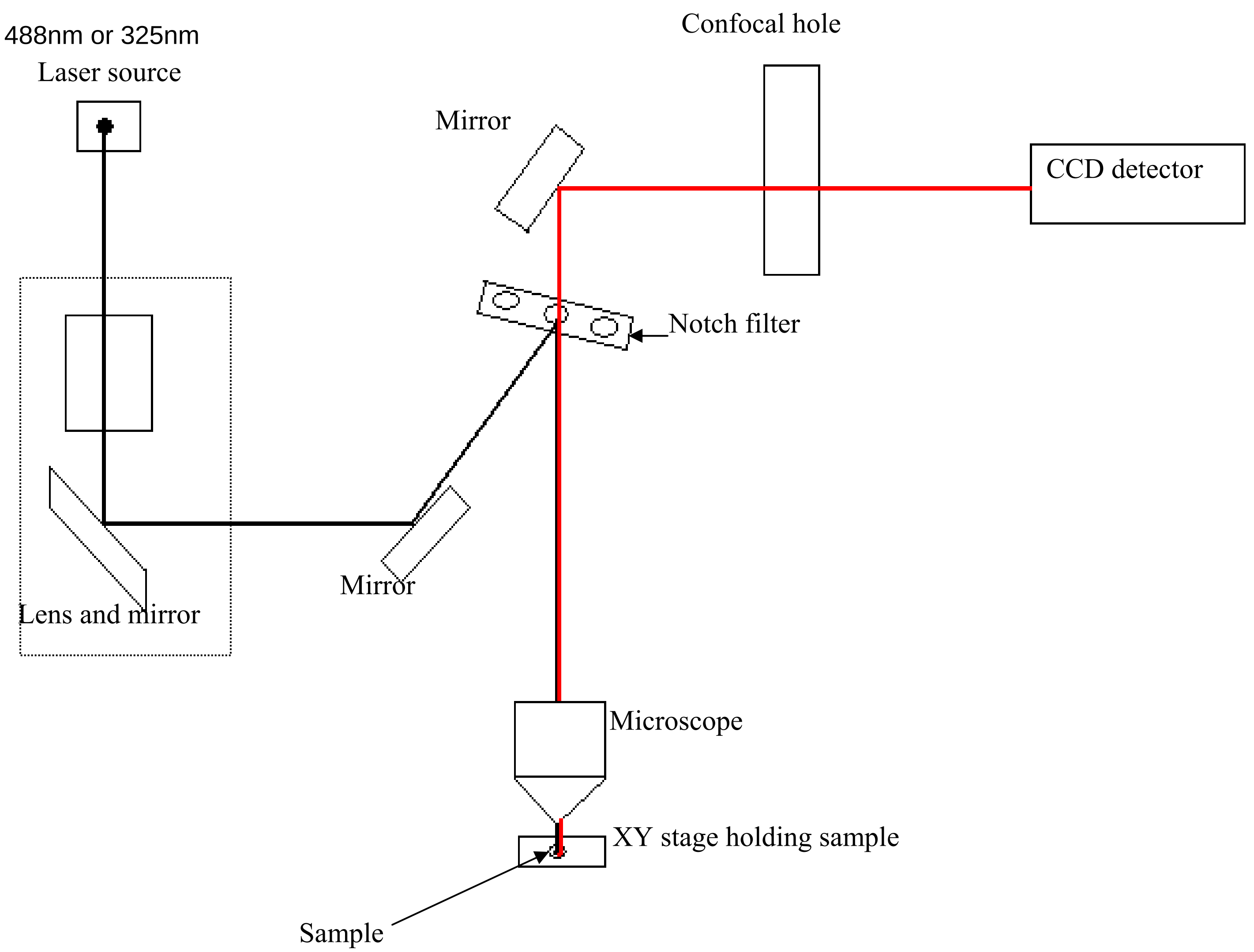






<u>Source:</u> *www.kosi.com*

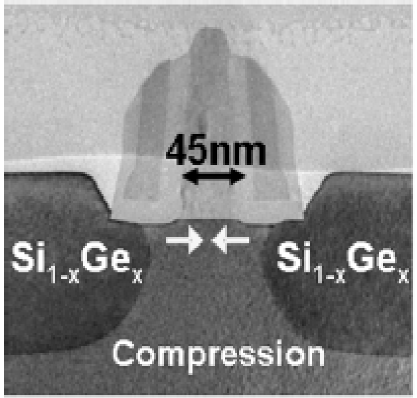
JY-Horiba LabRam 800 μRS System



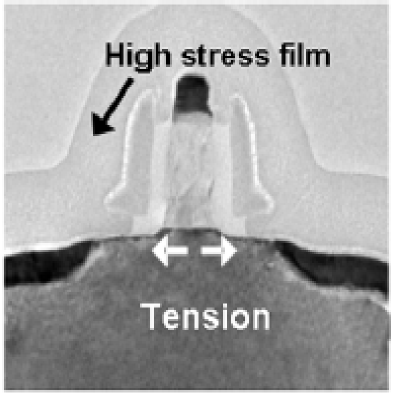
Strained Silicon CMOS Technology

"The industry cannot live without strain-engineering for enhanced mobility" *Semiconductor International, 2006*

- **Strained Si channels improve electron and hole mobilities.**
- **Greater current drive for less power.**



pMOSFET



nMOSFET

(Source: Thompson et al., Intel)

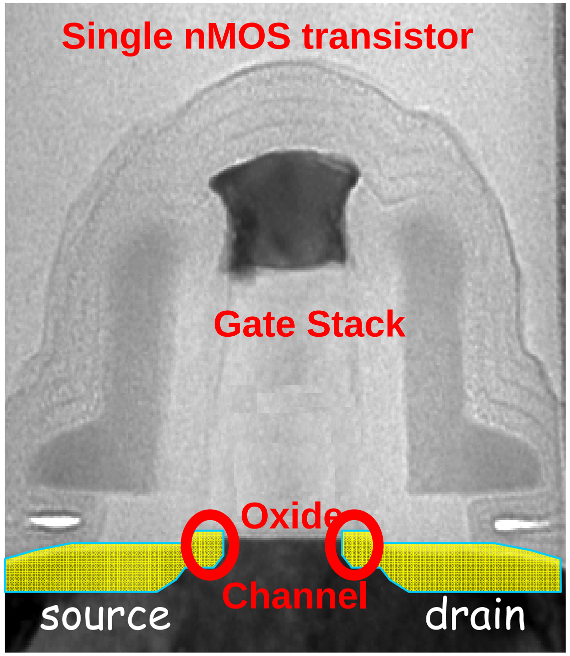
drain

(Source: Valencia, IBM)

How does strain affect heavily doped device regions?

Research Motivation

Source/drain extensions are one example



ITRS identifies 3 key requirements...

1) Increasingly shallow junction depth (x_j)

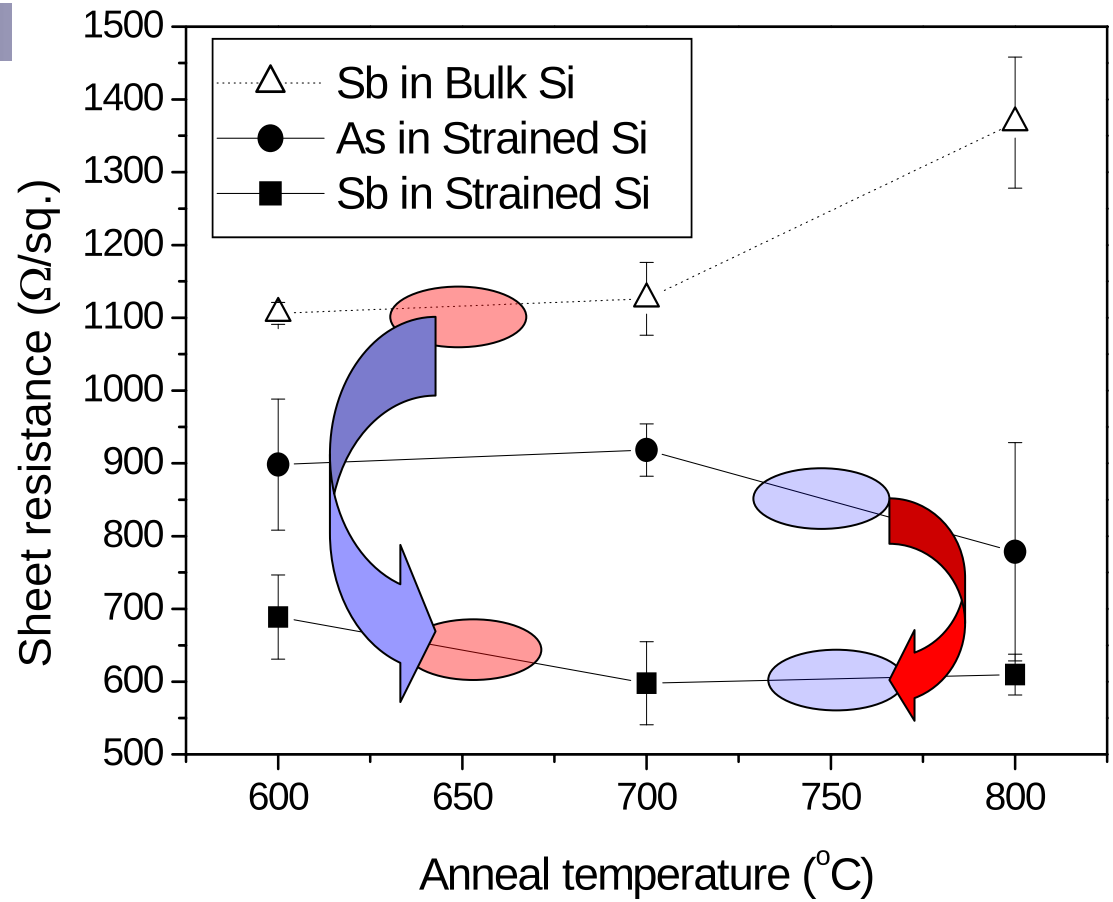
2) Increasingly steep junction profile

3) Maintain low resistance (R_s)

✓ **Importantly... Sb has the edge over As**

Sample Information

- 17 nm strained Si layer grown on a graded $Si_{0.83}Ge_{0.17}$ virtual substrate
- 43 nm strained Si layer grown on $Si_{0.80}Ge_{0.20}$ virtual substrate
- Antimony and Arsenic Ion Implantation
  - 2keV, 4e14cm^{-2} Sb
  - 2keV, 4e14cm^{-2} As
- Annealed @ 600, 700, 800^{0}C in N_2 ambient
- Comparison to bulk unstrained Si

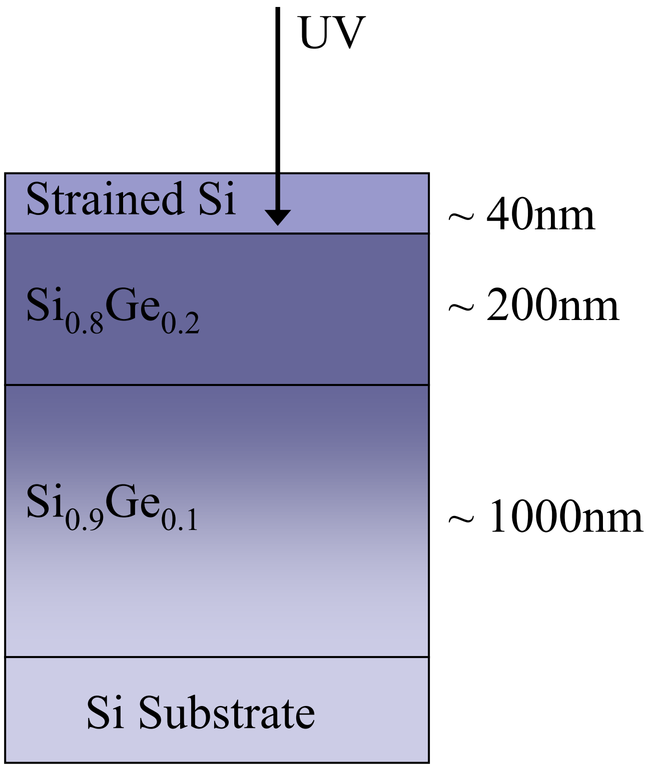


- Large R_s reduction for strain vs bulk for Sb doping
- Lower R_s for Sb doping compared to As in strained Si.
- Sb more highly activated than As in the presence of strain

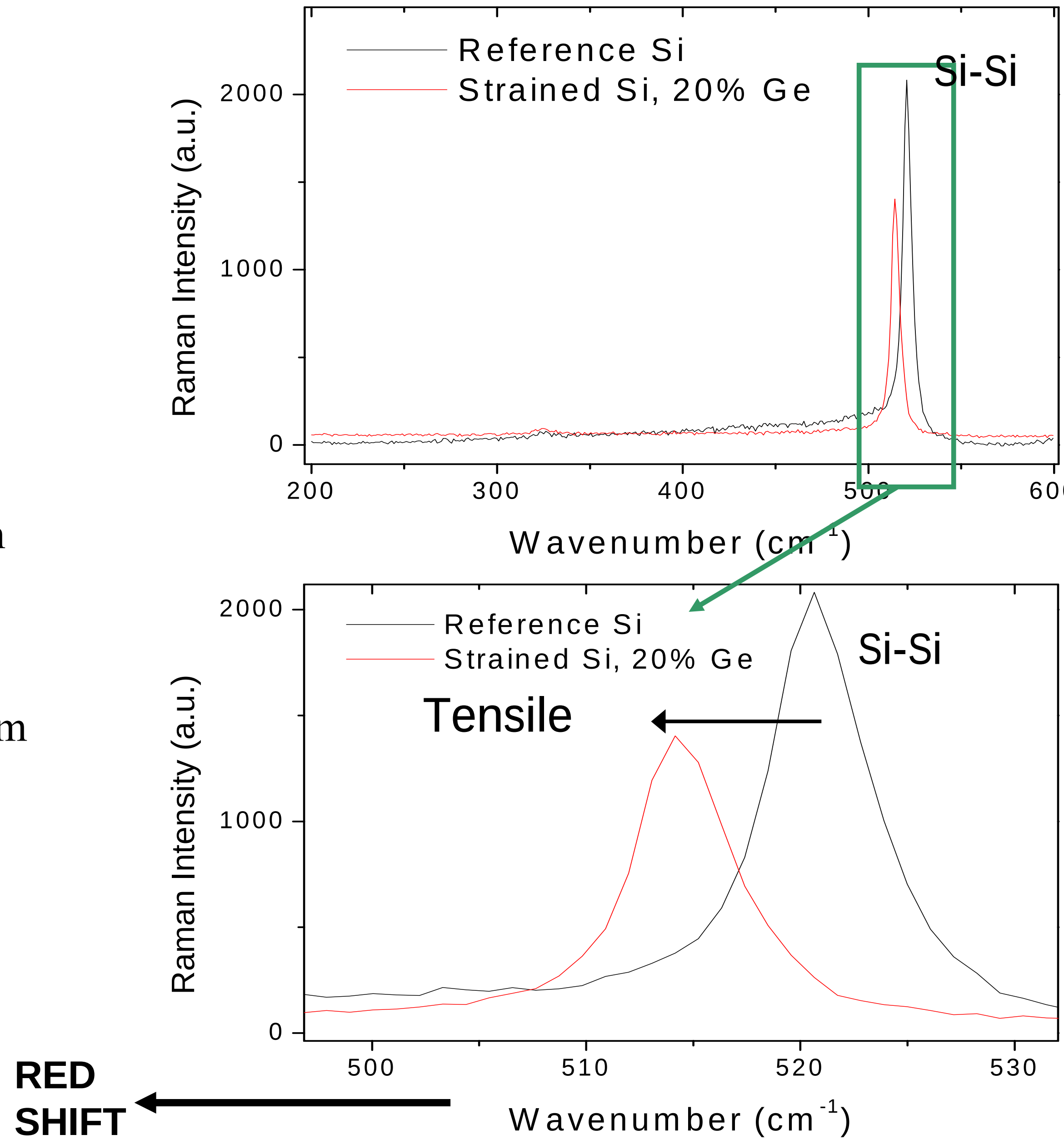
N. S. Bennett et al., Appl. Phys. Lett. ***89****, 182122 (2006)*

Raman Spectra: 325nm laser

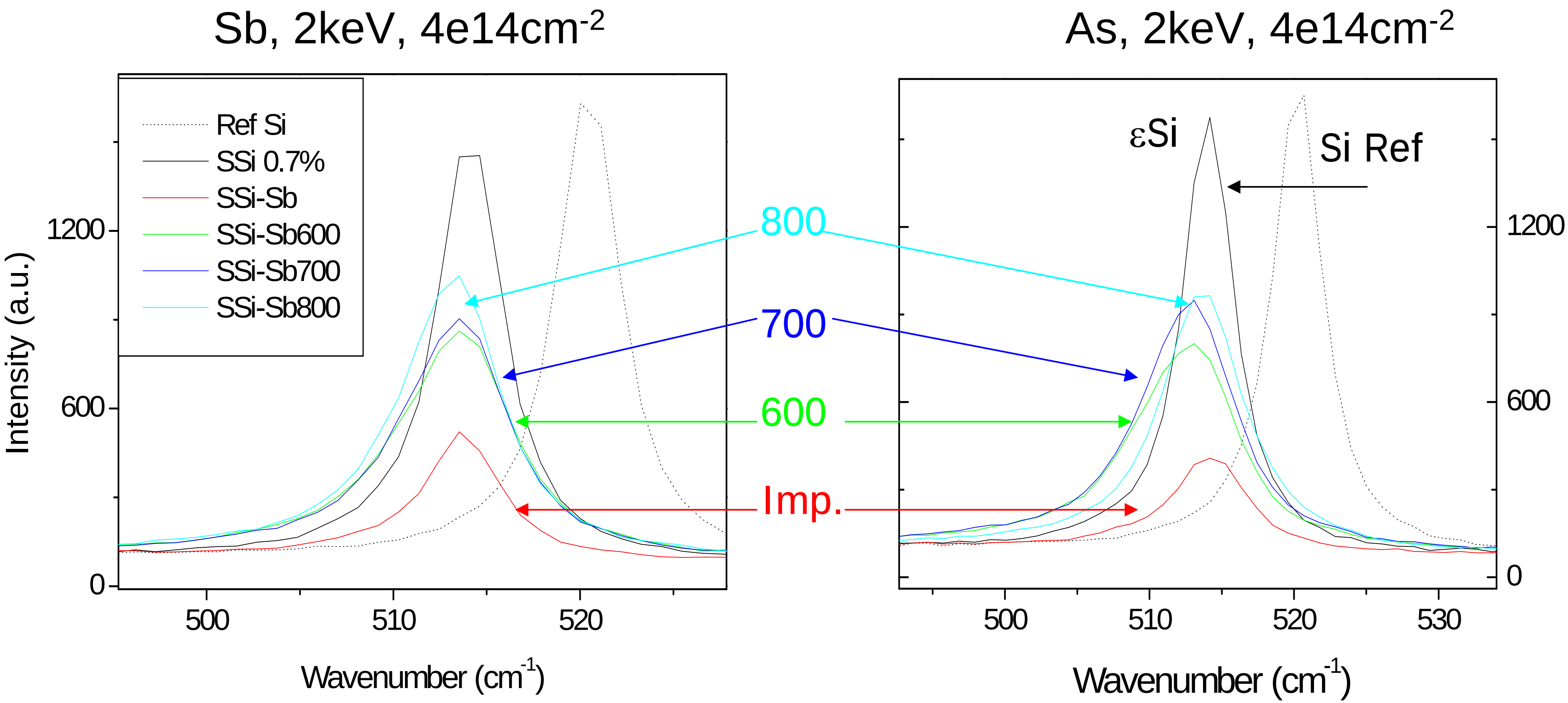
- 325 nm HeCd UV laser.
- $d_p \approx 9$ nm.



UV Laser penetration in SiGe structure

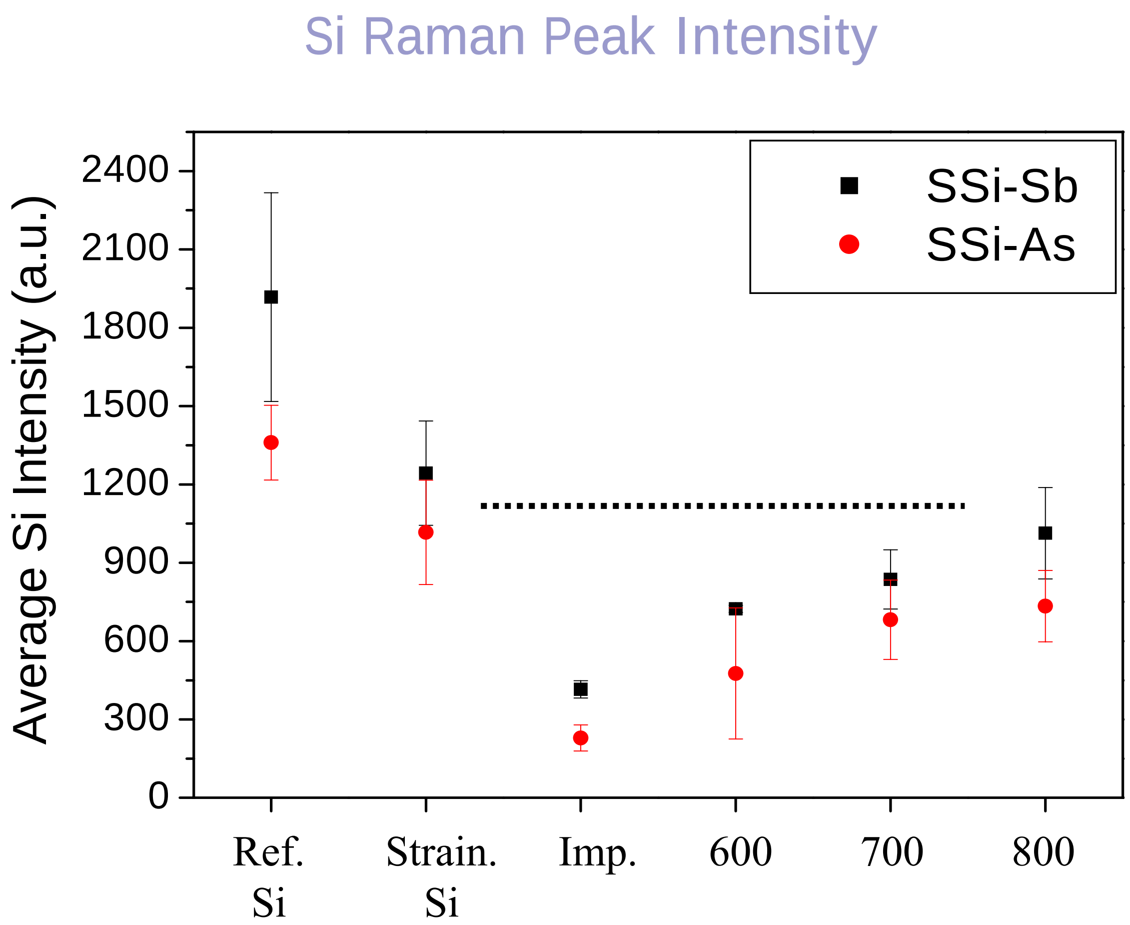


Raman Spectra: UV laser



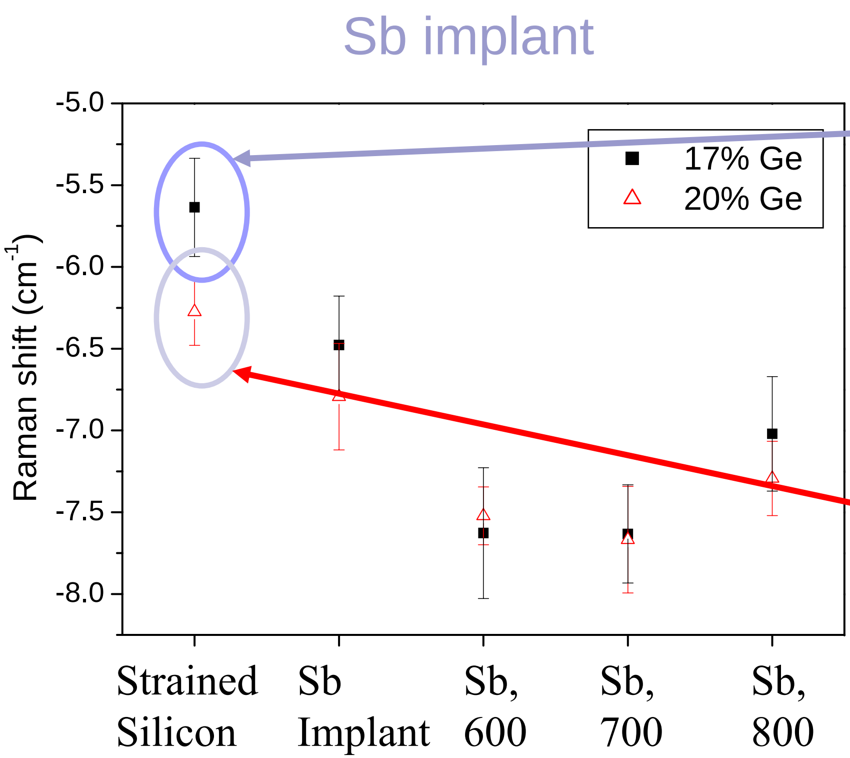
- Red-shift of Si peak indicates the presence of tensile strain in the Si cap layer
- Spectra of Sb and As implanted samples show similar behaviour with clear intensity variation with heat treatment.

UV Raman Spectra Analysis



- Si-Si peak intensity variation is consistent with lattice disorder introduced by ion implantation which recovers with heat treatment.
- Lattice recovery may not be complete following RTA at 800^{0}C for 10 sec.

UV Raman Si Peak Shift



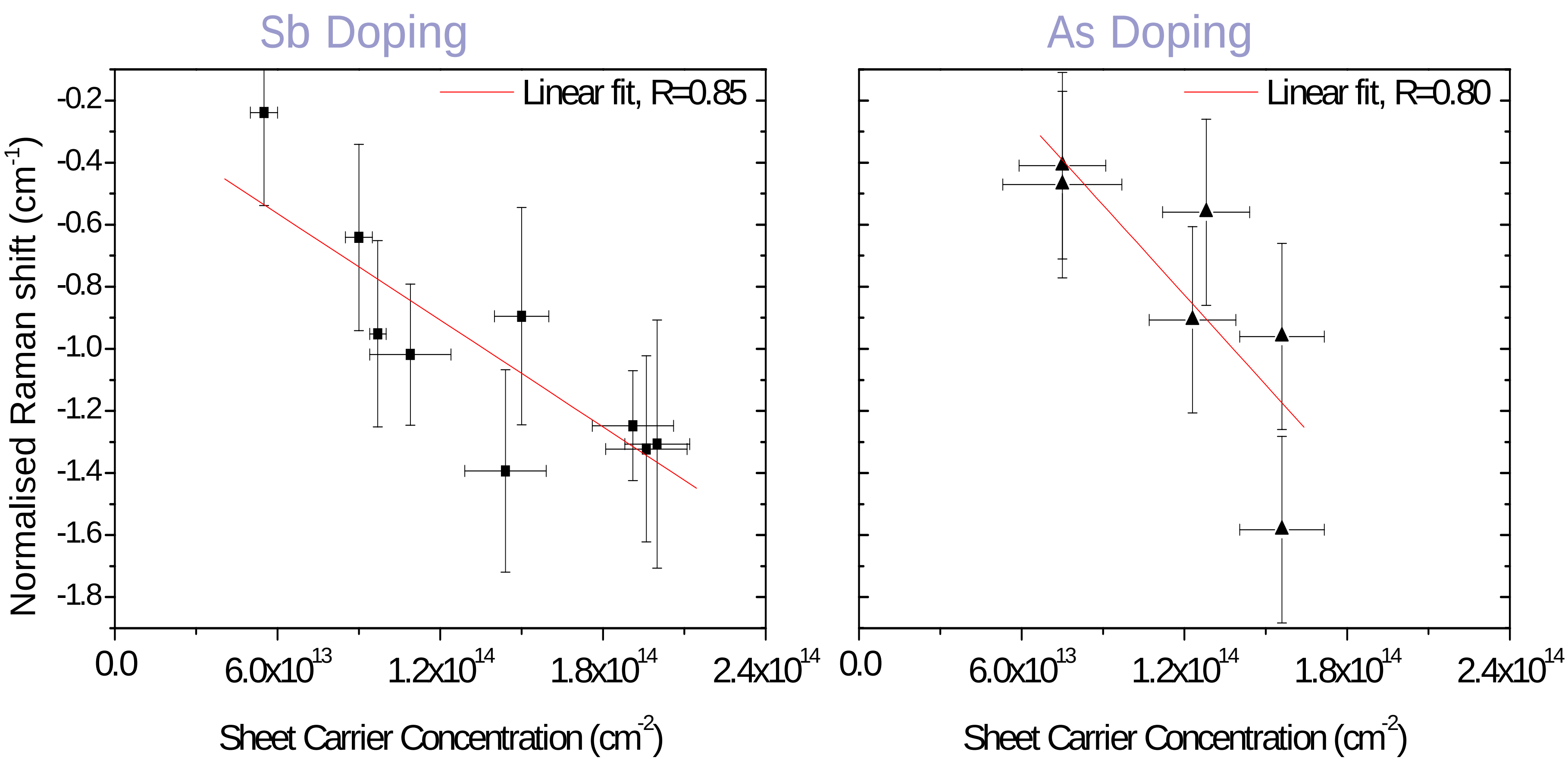
- Peak shift Relative to Unstrained Reference Si

- Biaxial stress $\sigma_{xx} = \sigma_{yy} = -\Delta\omega_{Si_{UV}}/4$ GPa
- Strained Si, 17% Ge:
  - $\Delta\omega_{Si_{UV}} = -5.64 \pm 0.3\ cm^{-1}$
  - $\Rightarrow \sigma = 1.4 \pm 0.1$ GPa
  - ε=0.77 ±0.06%
- Strained Si, 20% Ge:
  - $\Delta\omega_{Si_{UV}} = -6.27 \pm 0.2\ cm^{-1}$
  - $\Rightarrow \sigma = 1.57 \pm 0.1$ GPa
  - ε=0.86 ±0.06%

- Strain relaxation would be detected by a blue shift (higher wavenumber) of the Si Raman peak.
- But peak red-shift clearly *increases* following ion implantation and RTA

Ref: I. De Wolf, Semicond. Sci. Technol. ***11****, 139(1996)*

What is causing the net red shift of the Si peak position observed in the UV Raman spectra?



- Clear linear dependence between the normalised Raman shift and the sheet carrier concentration!

Why does doping cause a Raman shift?

- Cerdeira and Cardona* observed carrier-concentration related frequency shifts in the Raman spectra of both p-type and n-type Si.
- N-doping of Si alters the lattice deformation potential, effectively "softening" the lattice
  - $\Rightarrow$ lower phonon vibrational frequencies
  - $\Rightarrow$ Raman red-shifts
- Usually a very small effect in n-type Si
  - ✓ Only significant when doping concentration is large.
  - ✓ Which it is here!!! $10^{20} – 10^{21}$ cm^{-3} effective doping!!**
  - ✓ Independent of dopant type.

•* *F. Cerdeira & M. Cardona, Phys. Rev. B.* ***5****, 1440 (1972).*

•** *L. O'Reilly et al., INSIGHT-2007, Napa, California, U.S.A., May 6-9, 2007.*

Conclusions from Micro-Raman Spectroscopy

- Caution needed when using UV Raman for Si strain metrology in highly doped ultra shallow junction structures.
- For all implanted samples (strained and bulk substrates) there is a net red shift in the position of the Si-Si phonon mode.
- Confinement, stress and carrier concentration effects contribute to this shift.
- The observed anomalous Raman shift originates from the high levels of doping achieved in the samples.

Summary

- DCU’s combined suite of technologies provides versatile methodologies for advanced IC metrology.
- Virgin wafer through to completed circuit.
- Nanometre to mm probe depths.
- Virtually any materials combination!!!

Confocal μRS microscope

- ✓Allows rejection of radiation originating away from the focal point conjugate to the confocal aperture.
- ✓This radiation from the blue and red planes does not pass through the aperture, because they are not focussed in the confocal plane.
- ✓Raman radiation originating away from the sample depth of interest never reaches the entrance to the spectrograph
- ✓Acquired spectrum is specific to the depth of the sample in focus.