May , 2010

Radiation Effects on Emerging Electronic Materials and Devices

Radiation Effects in Emerging Materials

Overview

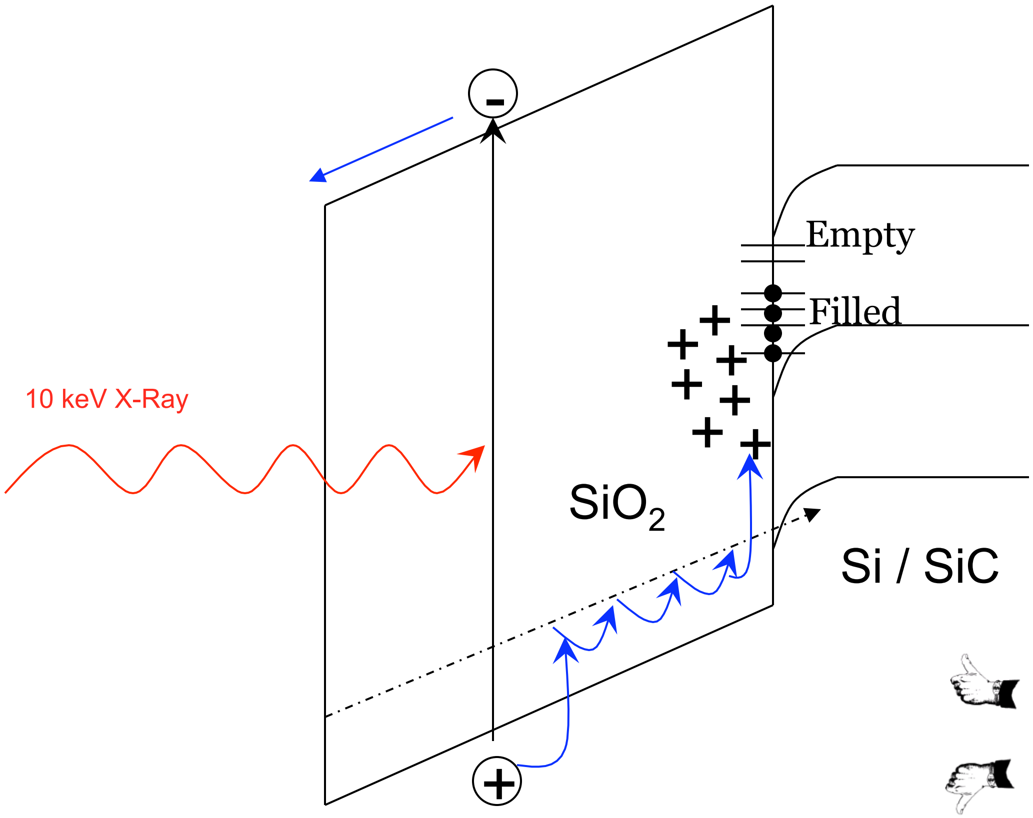
Leonard C. Feldman

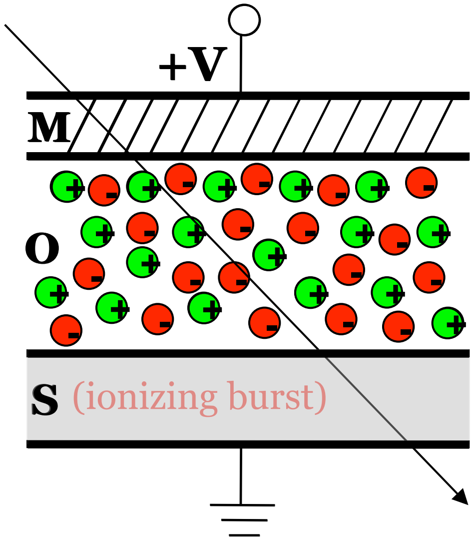
Vanderbilt University

And

Rutgers University

Ionizing radiation





- 👍 Generation of carriers at low fields
- 👎 Both e^- and h^+ → net trapping

Voltage shifts - as-oxidized/nitrided

$$^{a,b}\ \Delta N_{ot} = -C_{ox}\frac{\Delta V_{mg}}{qA}$$

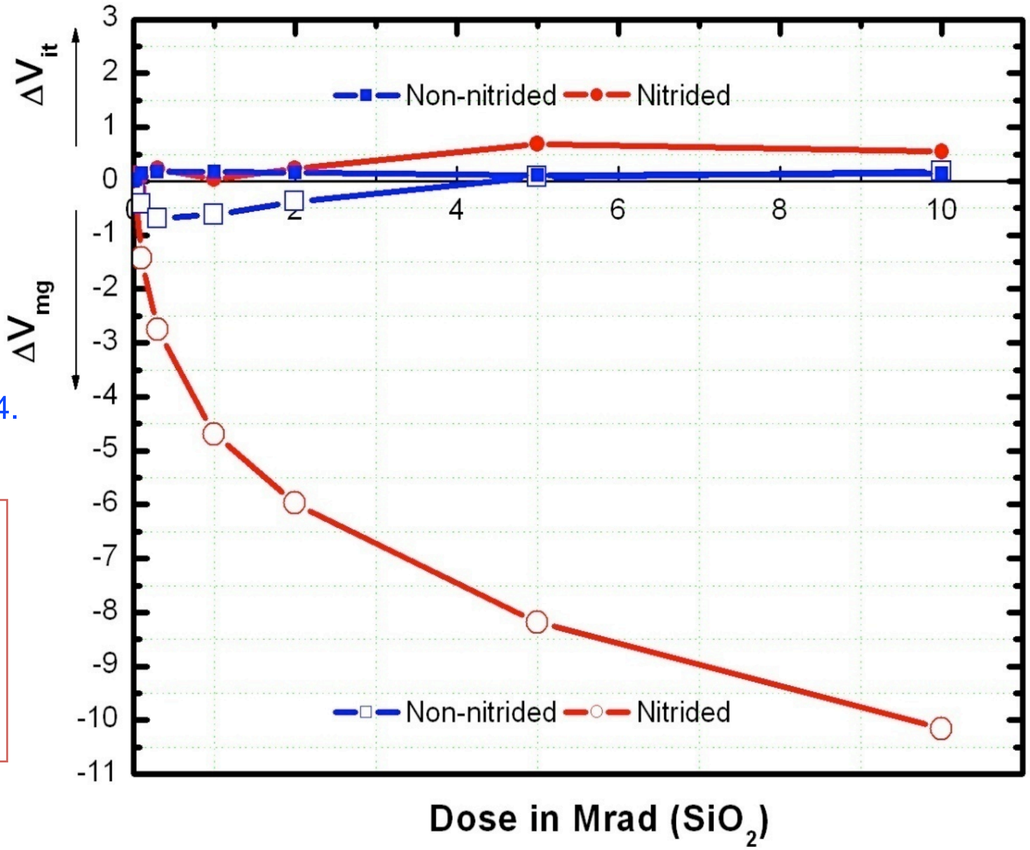
$$^{a,b}\ \Delta N_{it} = C_{ox}\frac{(\Delta V_{fb} - \Delta V_{mg})}{qA}$$

[a]P. S. Winokur et al., IEEE TNS, vol. 31, pp. 1453, 1984.
[b]P. J. McWhorter et al., APL, vol. 48, pp. 133, 1986.

For nitrided, at 10 Mrad(SiO_2),

ΔN_{ot} ~ 6.3 x 10^{12} cm^{-2},

ΔN_{it} ~ 3 x 10^{11} cm^{-2}



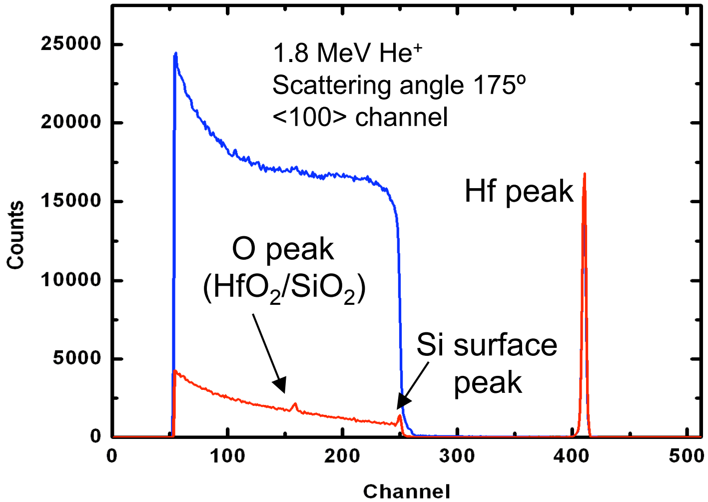
Dixit *et al.*, IEEE TNS, vol. 53, p. 3687, 2006

Key results

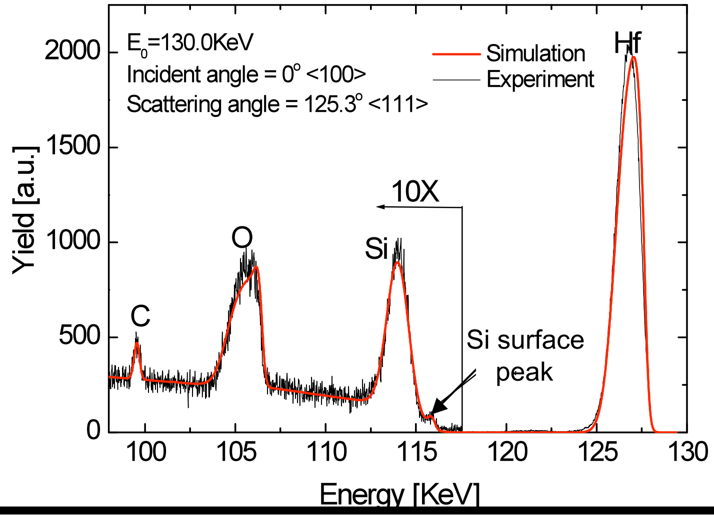
- ➢ First observation of enhanced positive charge trapping in nitrided samples
- ➢ Turnaround in the non-nitrided samples owing to charge compensation

Materials analysis - HfO_2/SiO_2 IL/Si

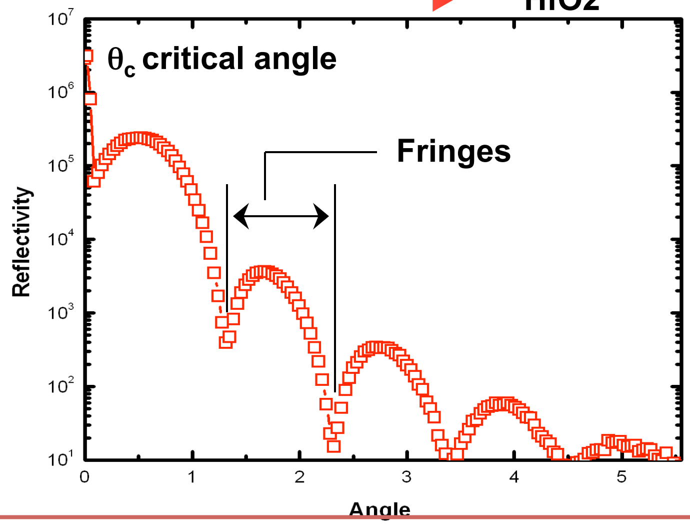
RBS/Channeling → t_{HfO2} & t_{SiO2}



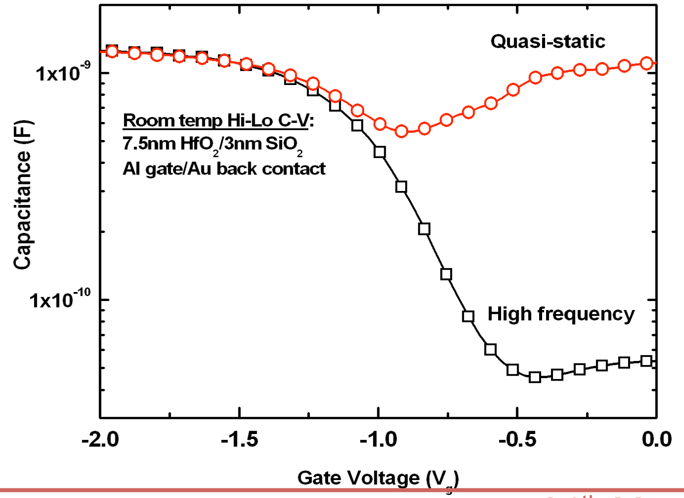
MEIS → t_{HfO2}, t_{SiO2} & Si in HfO_2



XRR → t_{HfO2}



C-V → t_{HfO2}, t_{SiO2} & Si in HfO_2



Dixit *et al.*, manuscript to be submitted to JAP, 2008

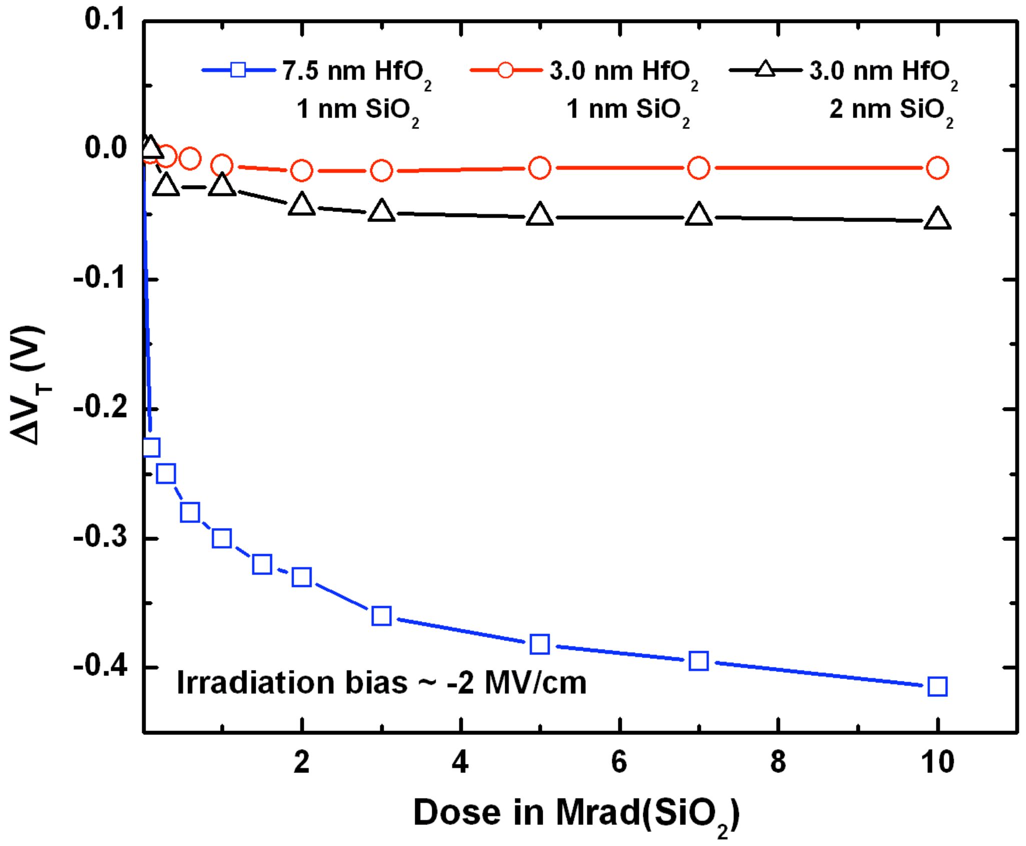
Summary: MURI ’06 -’10

Gennadi Bersuker, R. Garfunkel, et al.

The following components for assessing gate stack instabilities under external perturbations were developed:

- **Test structures:** required for advanced measurements
- **Techniques**: Evaluation of instabilities
- **Analysis:** Noise, charge pumping measurements
- **Methodologies:** Reliability assessments
- **Mechanisms**: High-k gate stack degradation and breakdown

Total dose results comparison



Irradiation Bias ~ -2 MV/cm

Dixit *et al.*, manuscript to be submitted to APL, 2008

Key results 3 nm HfO_2/2 nm SiO_2

- IL O leaching ↑ 7.5 nm HfO_2 (exposure t ↑ at higher temp. growth[a,b])
- I-V sweeps modify the charge (~ 50%) (border traps in the SiO_2 IL[c])
- Residual V_T after stabilization (traps in HfO_2 and/or away from interface)

[a] Bersuker *et al.*, JAP, vol. 100, p. 094108, 2006,
[b] Ryan *et al.*, APL, vol. 90, p. 173513, 2007,
[c] Fleetwood *et al.*, *IEEE TNS,* vol. 39, p. 269, 1992.

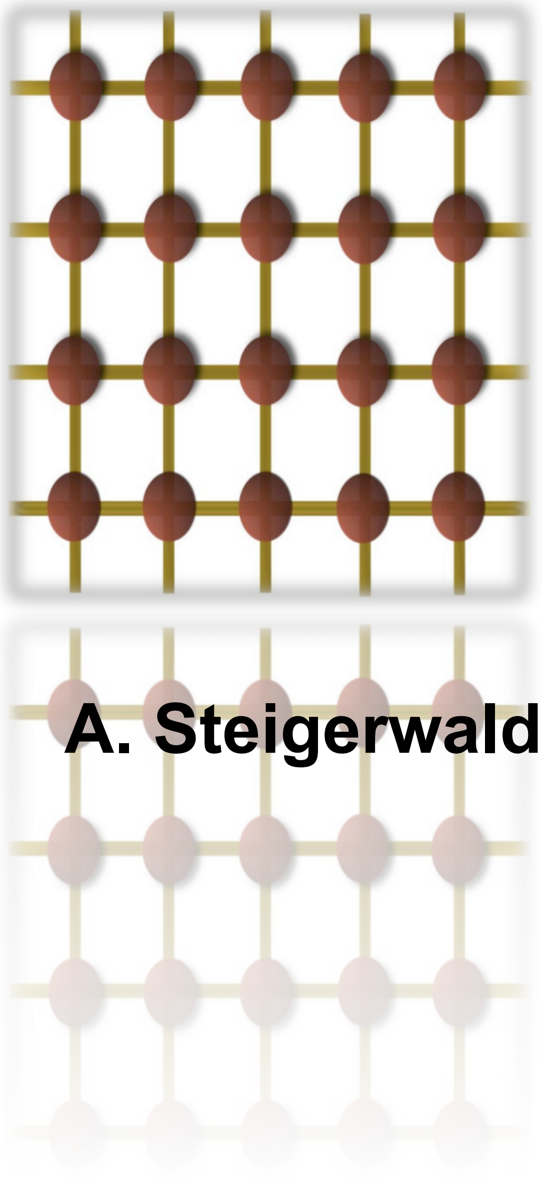
Conclusions - HfO_2 based MOSFETs

- 3 nm/1 nm devices radiation tolerant and resistant to constant-voltage stress
- Total dose comparison between 7.5 nm/1 nm and 3 nm/2 nm MOSFETs suggest substantial hole trapping in the SiO_2 IL
- Residual V_T shift suggest the presence of some of the holes trapped charge away from the interface, probably in the HfO_2 bulk

STUDENT EVOLUTION

Kyle McDonald-SANDIA—Radiation Effects
Jon. Bennett- INTEL
Sarit Dhar*- CREE—SiC MOS Research
Sriram Dixit *- INTEL-Reliability
John Rozen*- CRIEPI (Japan)>IBM(?)—Si-MOS

*-Funded partially or totally from MURI

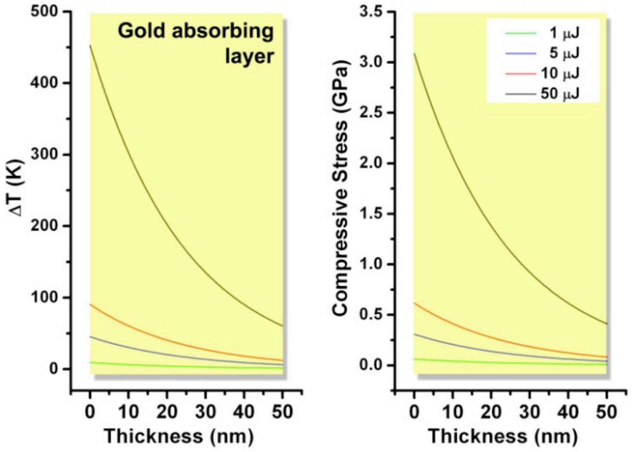


Surface generated acoustic waves for semiconductor defect analysis

A. Steigerwald, J. Qi, Y. Xu, A.B. Hmelo, K. Varga, L. C. Feldman, N. Tolk

Coherent Acoustic Phonon Pulses

Strain pulse launched from surface absorption of light



Calculated temp. rise and initial thermal vs pulse energy
(Au 50nm, lambda 500nm, spot size 1mm)

$$\sigma_{33} = 3\frac{1-\nu}{1+\nu}B\eta_{33} - 3B\beta\,\Delta T(z)$$

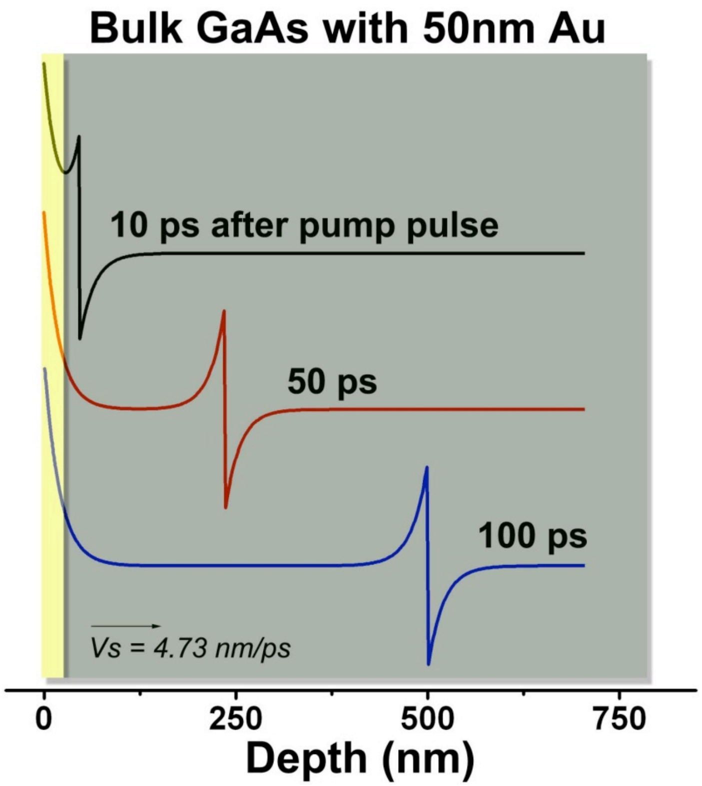
$$\rho\frac{\partial^2 u_3}{\partial t^2} = \frac{\partial \sigma_{33}}{\partial z} \qquad \eta_{33} = \frac{\partial u_{33}}{\partial z}$$

❑ Absorption of fs pulse gives near instant ΔT

❑ Two laser systems:

- Ti:Saph ➔ 1 nJ/pulse ➔ Mpa
- Amplifier ➔ 1 μJ/pulse ➔ Gpa

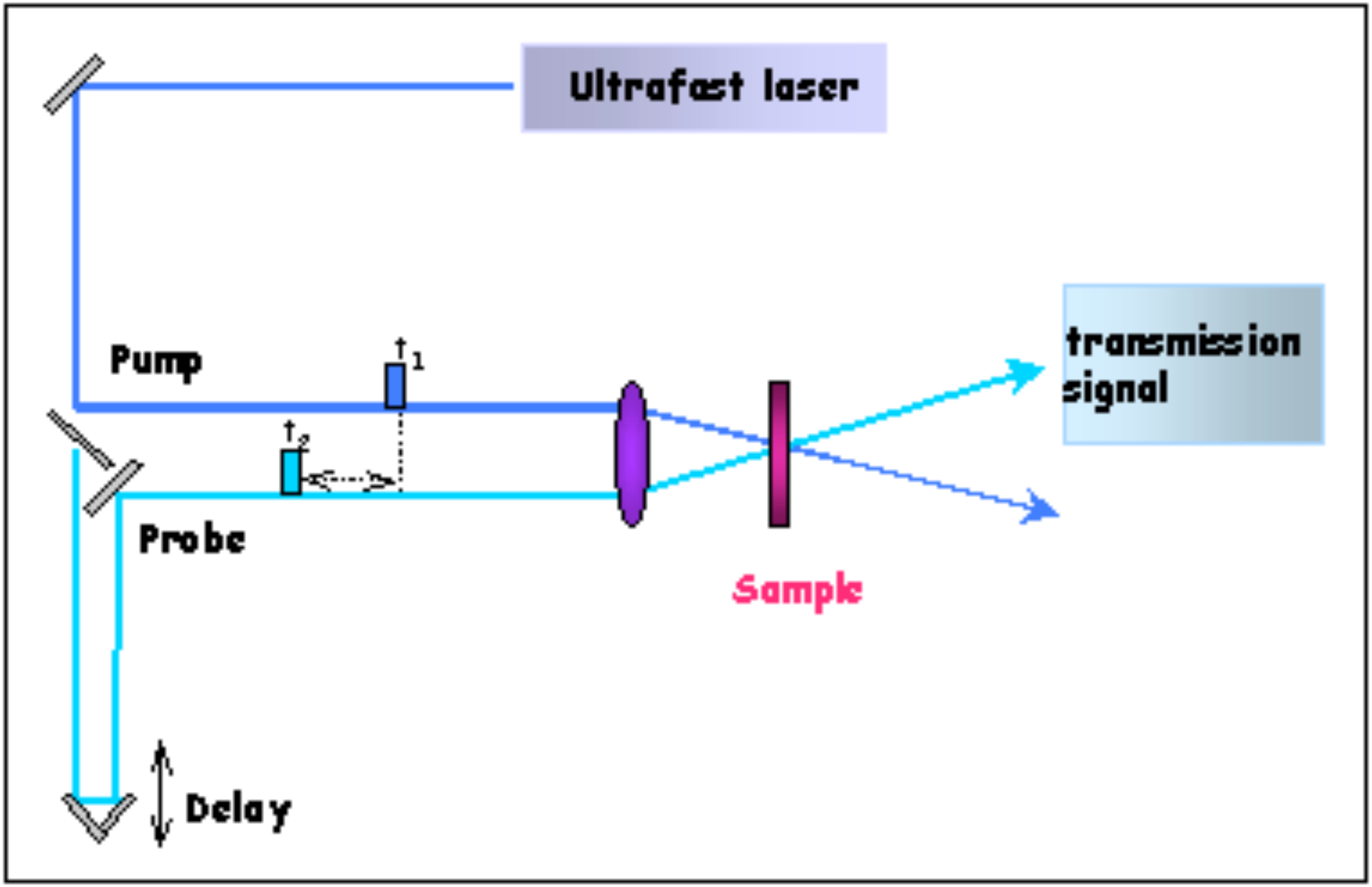
❑ Strain evolves from initial thermal stress according to elasticity equations



1. **Traveling ~10 nm “layer” of Δn**

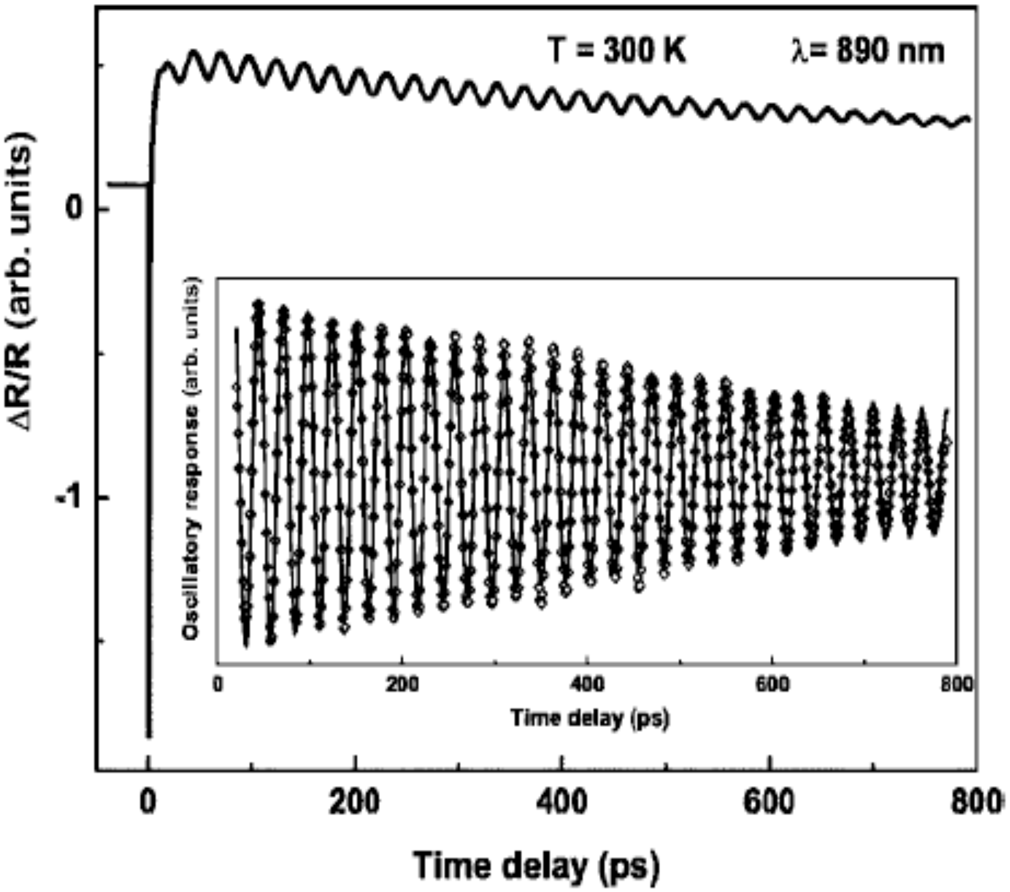
2. **Picosecond change in lattice constant, band structure, density…..**

PUMP-PROBE SPECTROSCOPY



Characterization of Materials

Strain wave acts as a travelling "mirror"



Thomsen, et al. PRL (1984), PRB (1986)

- ❑ **Strain wave - traveling optical discontinuity**
- ❑ **in a pump probe setup an oscillatory component arises**
- ❑ **Oscillations may be analyzed to depth-characterize material**
  - **complex index of refraction N=*n* + *ik***

$$T = \lambda/(2nVs\cos\theta),$$

$$\frac{\Delta R}{R_0} \approx Ae^{-t/\tau}\sin\left(\frac{2\pi}{T}t+\varphi\right),$$

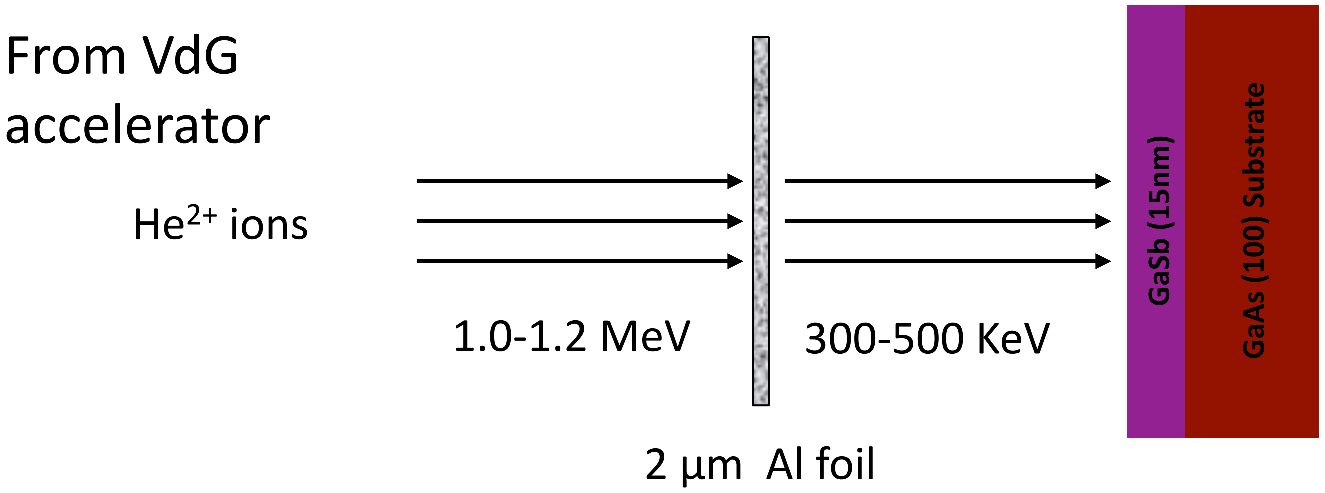
Depth-dependent defect profiles

He$^+$ implantation into GaAs wafer

☐ **Can we perform depth dependent defect analysis?**

- **Already known that defects modify N**

☐ **Ion implantation handy for causing damage**



From VdG accelerator

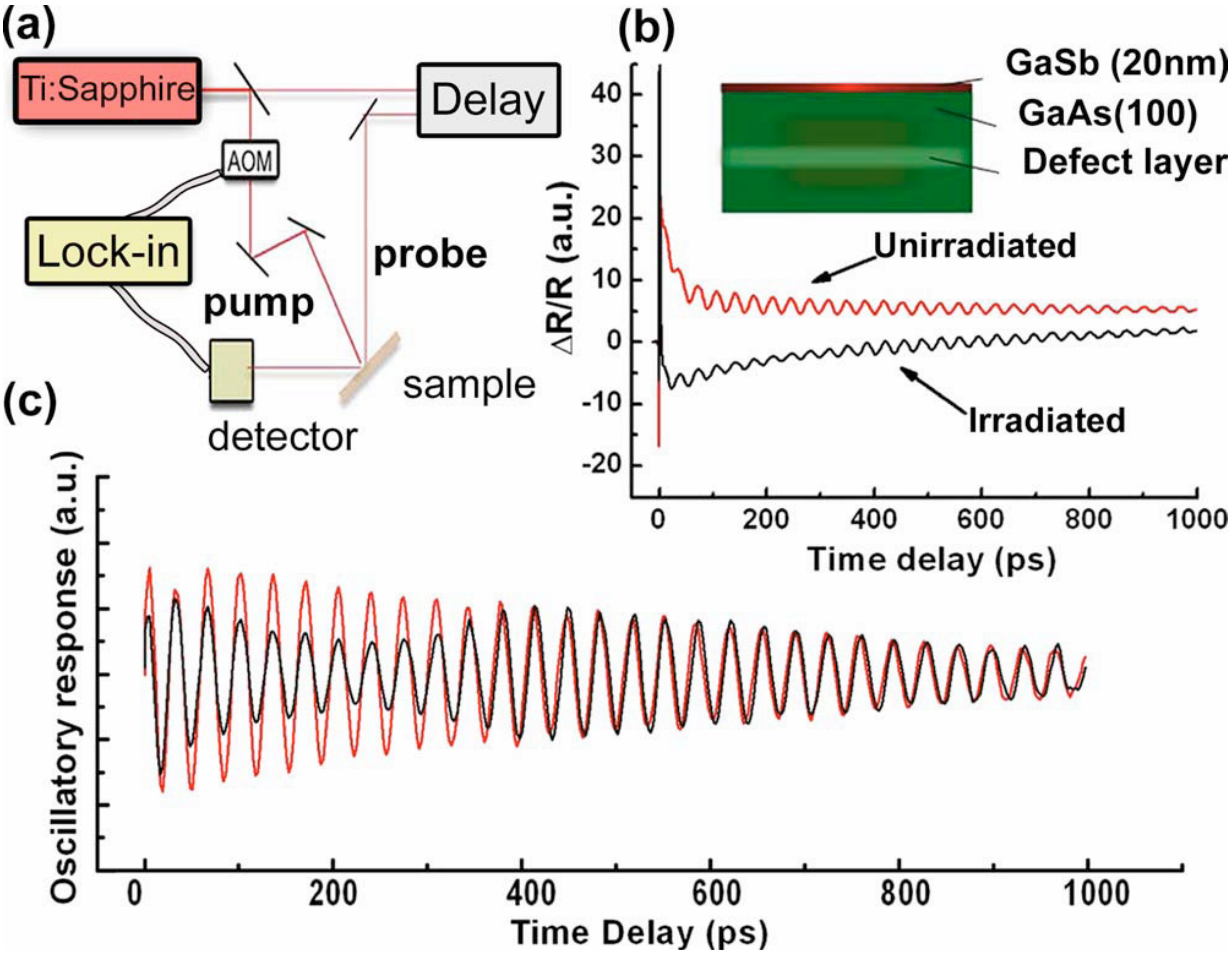
He^{2+} ions

1.0-1.2 MeV

300-500 KeV

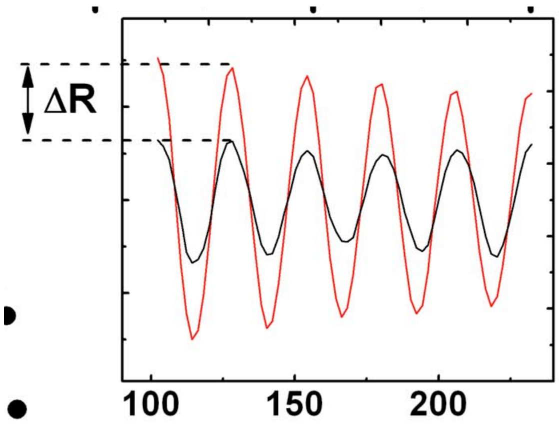
2 μm Al foil

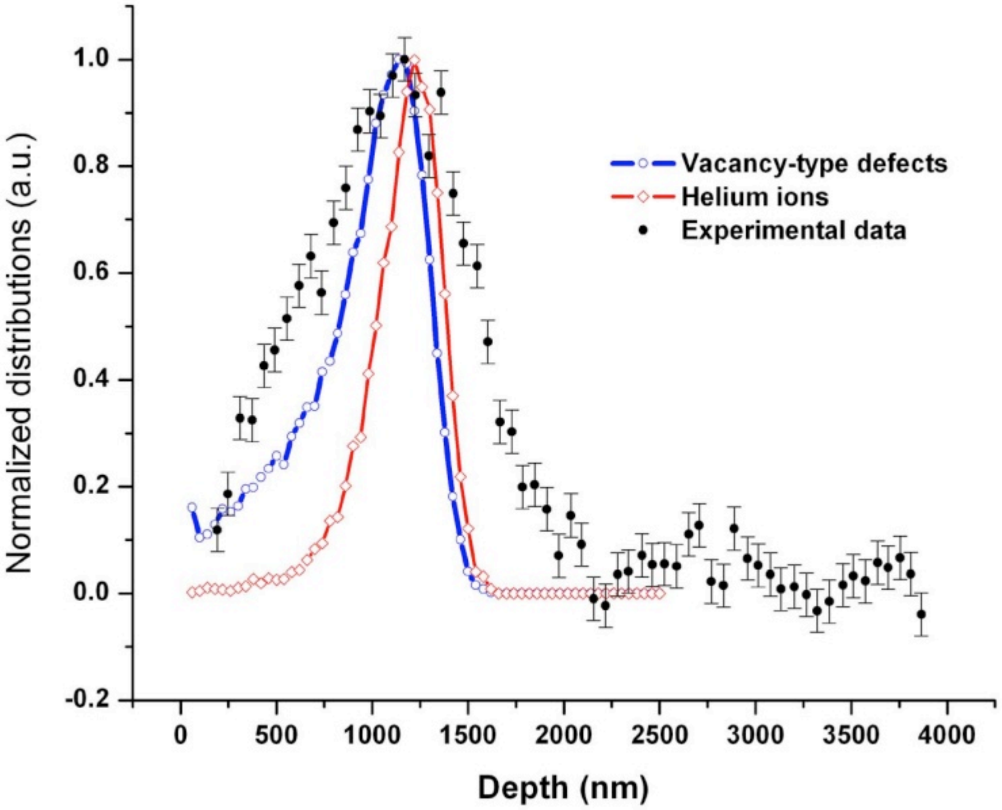
☐ **Dominant effect to create vacancy, interstitial defects**


(a)
Ti:Sapphire
Delay
AOM
Lock-in
probe
pump
sample
detector
(b)
GaSb (20nm)
GaAs(100)
Defect layer
Unirradiated
Irradiated
ΔR/R (a.u.)
40
30
20
10
0
-10
-20
0
200
400
600
800
1000
Time delay (ps)
(c)
Oscillatory response (a.u.)
0
200
400
600
800
1000
Time Delay (ps)

Profile broader than predicted

Optical dependence on defect population unknown

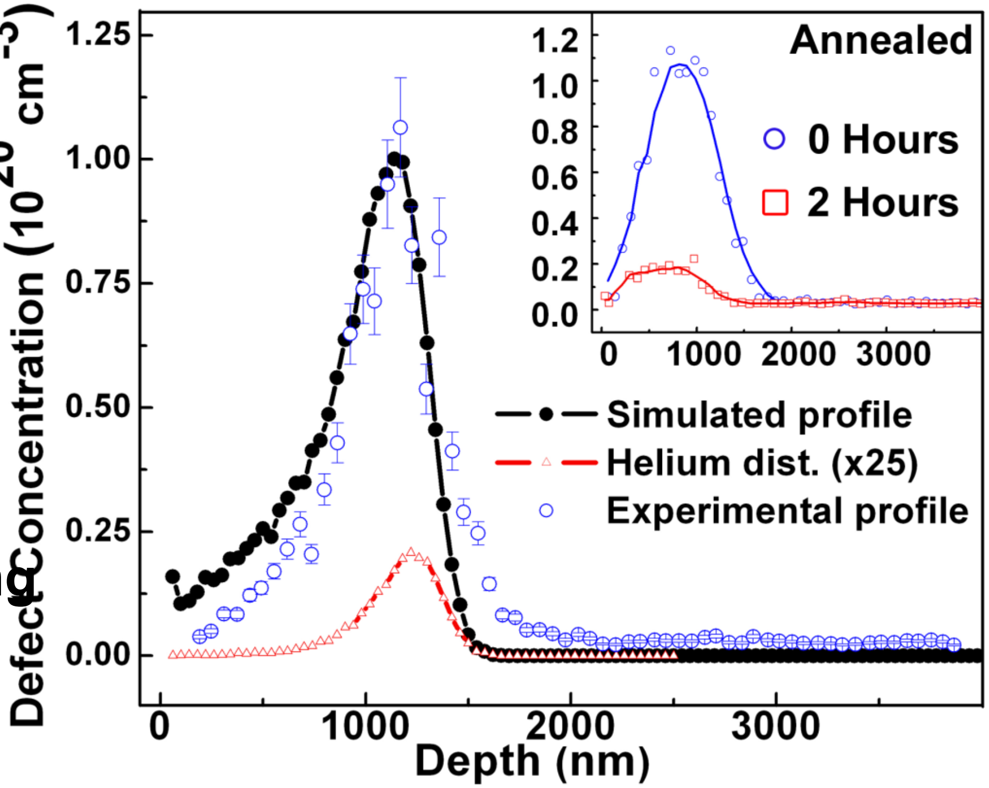




NOTE: Band gap modification deeper than damage

Quantitative Profiling

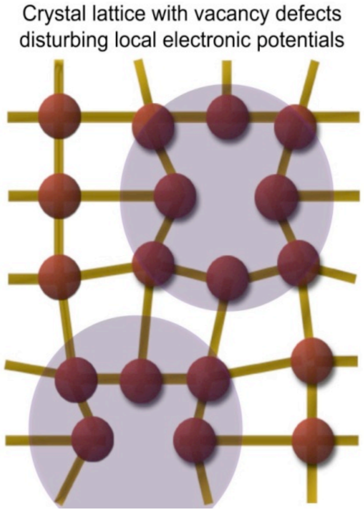
- ☐ **Repeat measurement for many different ion doses**
- ☐ **Establish relationship between amplitude change and defect concentration**
- ☐ **Map previous profile using established dependence**
- ☐ **Nondestructive, non-invasive approach**



[redacted]

A. Steigerwald *et al.*, Applied Physics Letters 94, 111910 (2009)

How do defects effect optical signal?

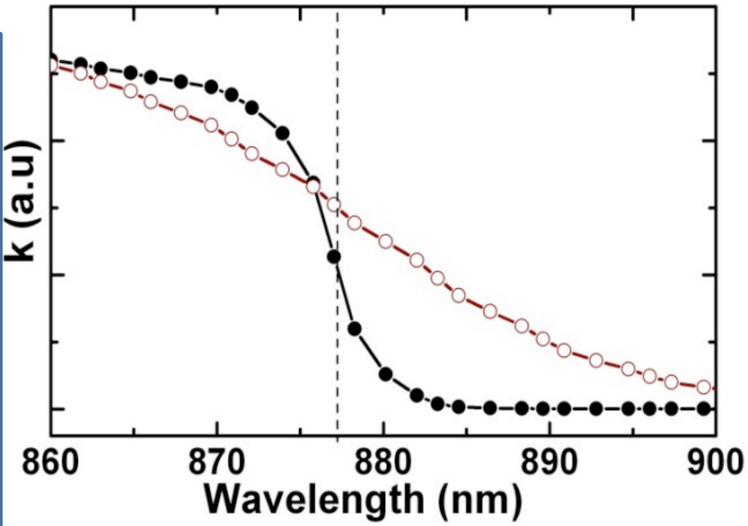


Crystal lattice with vacancy defects disturbing local electronic potentials

$\Delta R/R \sim dn/d\eta; \quad dk/d\eta$

$$\frac{dn}{d\eta} \propto \frac{dn}{dE}\frac{dE}{d\eta}, \frac{dk}{d\eta} \propto \frac{dk}{dE}\frac{dE}{d\eta}$$

η= strain; $E = E_{photon} - E_g$



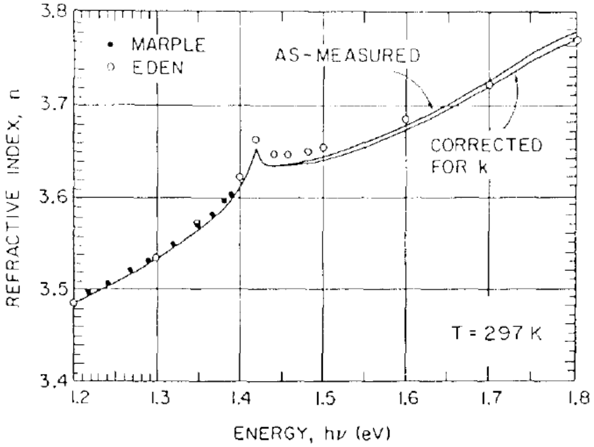


FIG. 31. Refractive index *n* for a high-purity GaAs sample (weakly *N*-type, $n_0 \simeq 5 \times 10^{13}$ cm^{-3}), as deduced by Sell *et al.*[207] from two-beam reflectance measurements at 297 K. Data obtained by Marple[203] from refraction measurements are shown for comparison. Shown also are points calculated by Eden,[208] from Kramers–Kronig analysis.

- ☐ **Lattice relaxation effects around defect sites**
- ☐ **D.O.S. and optical spectra broadened**
- ☐ **Amplitude reduced through photoelastic coef.**

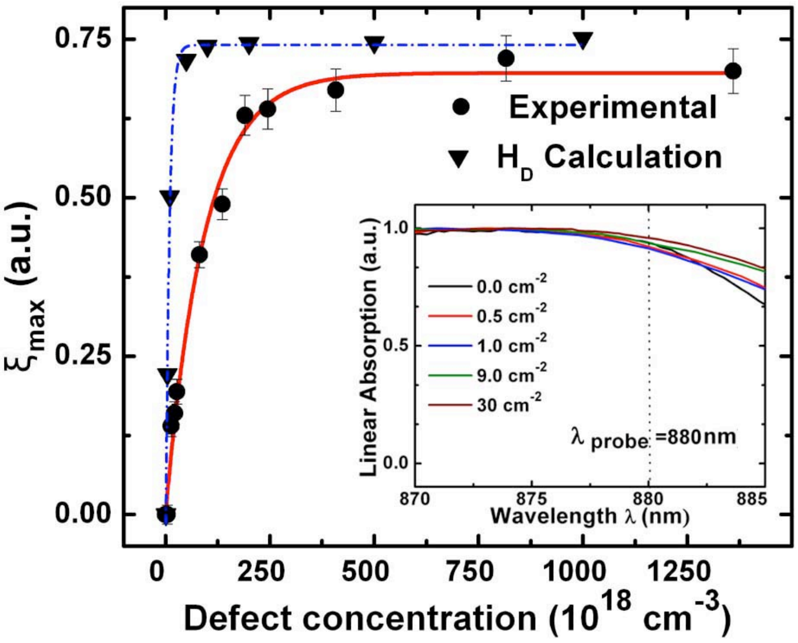
Determine growth of bandtailing versus defect concentration?

Logarithmic dependence shown

☐ Increases rapidly at onset near 10^{18} cm^{-3} in GaAs system

☐ Saturates well below total disorder limit

☐ Attributed to zone overlap



Characterization of electronic structure as function of defect concentration

Summary –
Coherent Acoustic Phonons

☐ Able to measure depth-dependent defect profiles in non-destructive, non-invasive manner

☐ Has wide applicability to different material/defect systems

☐ Ability arises from modification of electronic structure (dn/dE) by defects

☐ Sensitive probe to electronic structure modification