Femtosecond Studies of Wide Bandgap Semiconductors for Ultraviolet Emitter and Detector Applications

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Motivation

- **Why Femtosecond Nonlinear Optical Techniques?**
- Provide a tunable source in the wavelength region of interest, 225-375 nm
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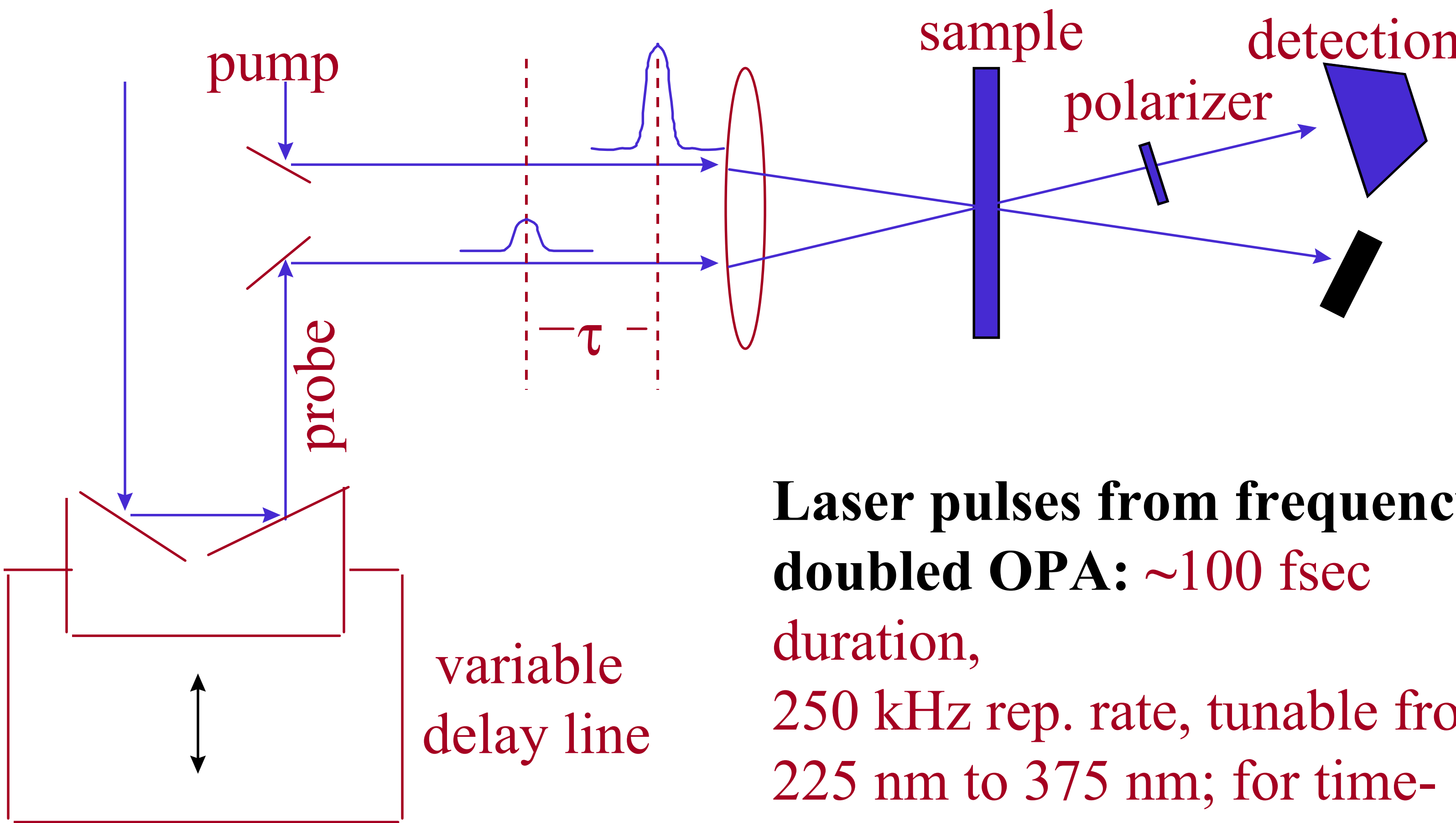
- Enable time-resolved studies of carrier relaxation, recombination, and transport processes in GaN and AlGaN materials

Experiment

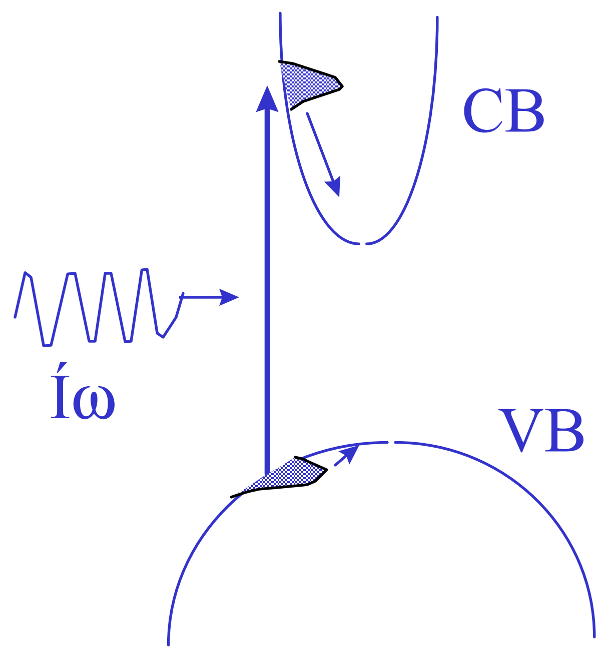


Laser pulses from frequency doubled OPA: ~100 fsec duration,
250 kHz rep. rate, tunable from 225 nm to 375 nm; for time-resolved transmission, reflection, and electroabsorption.

Time-resolved Reflectivity and Transmission

$$\Delta R \propto \Delta\varepsilon_1(\omega) = \frac{2}{\pi}\int_0^\infty \frac{\omega'\Delta\varepsilon_2(\omega')d\omega'}{\omega'^2 - \omega^2},$$

$$\Delta T \propto \Delta\varepsilon_2(\omega) \sim -\varepsilon_2(\omega)\{f_h(E_h(\omega)) + f_e(E_e(\omega))\}$$



In the parabolic band approximation:

$E_e/E_h = m_h/m_e$ and $f_n \propto m_n^{3/2}$

So we see primarily electrons.

Comparison of non-LEO, LEO and double LEO material

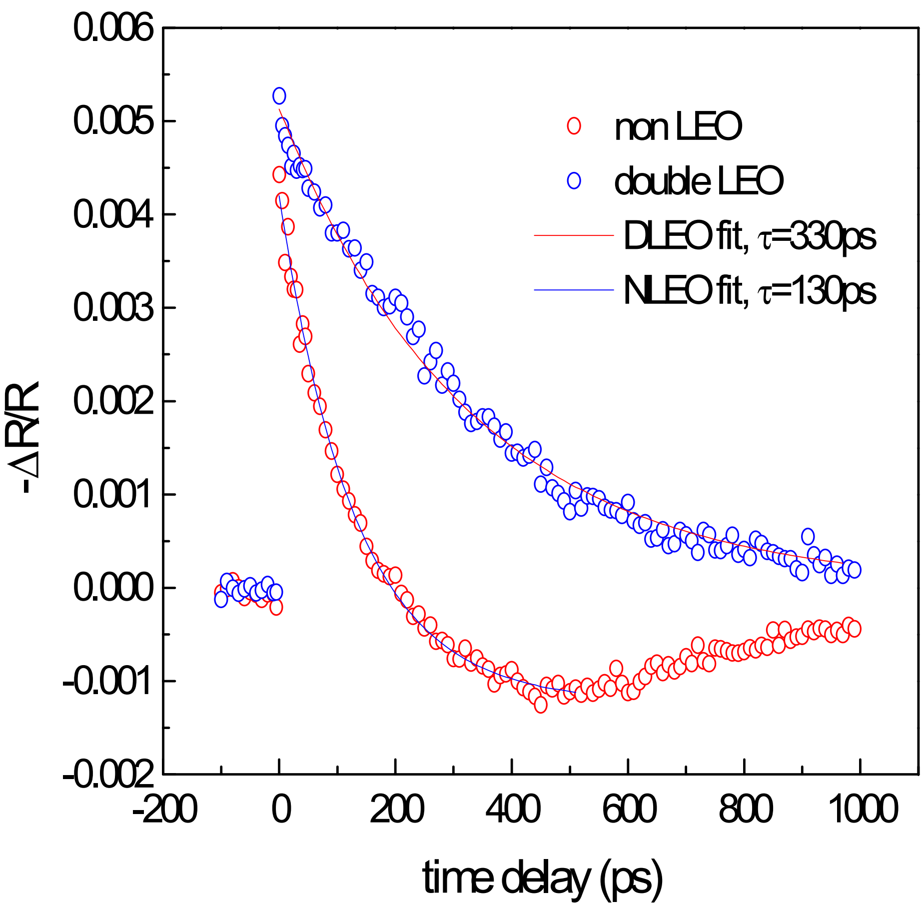
Background: Lateral Epitaxial Overgrowth (LEO) is a growth technique used to reduce the number of threading dislocations in GaN on sapphire or silicon.

Motivation: Determine to what extent a significant reduction in threading dislocations improves the carrier lifetime.

Comparison of non-LEO and double LEO decays in GaN

- Longer lifetime and increased luminescence efficiency in the DLEO material implies reduction in threading dislocation density

- Higher quality material may lead to higher detector responsivity, better spectral rejection, lower reverse leakage current for avalanche photodiodes, better laser performance



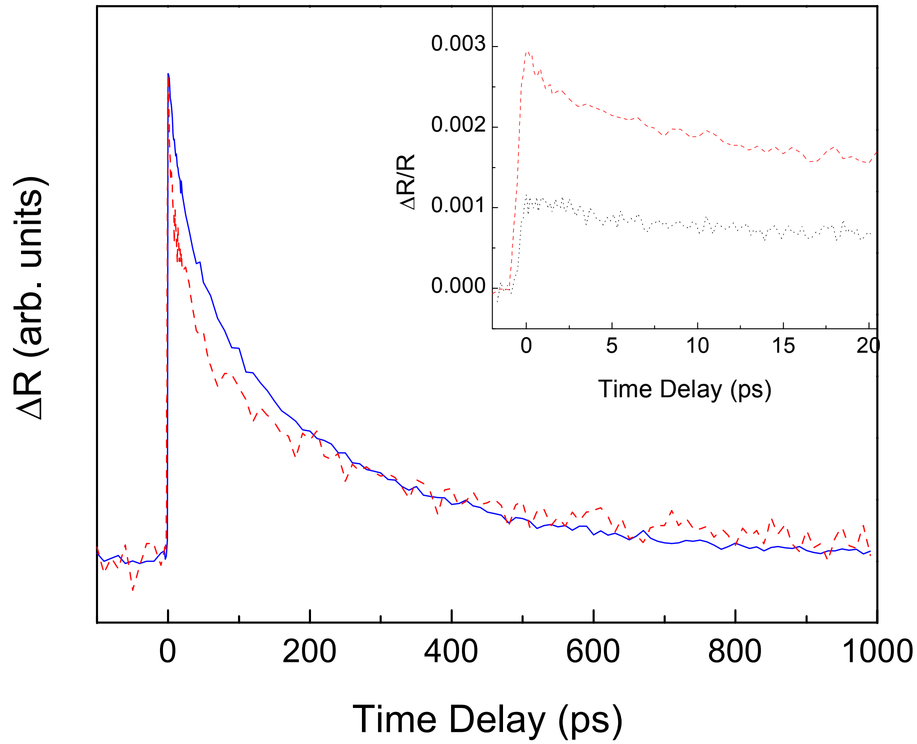
Samples provided by M. Razeghi, Northwestern University

Carrier Dynamics in LEO GaN

For excitation at 347 nm, the hot electron distribution (excess energy > 100 meV) cools primarily by transfer of energy to both the cold photoexcited hole distribution through electron-hole scattering, and to the lattice through electron-LO phonon scattering.

The fact that the decay rate increases with decreasing carrier density suggests less screening of the LO phonon scattering.

When the density is further halved (inset), the initial decay becomes too fast to resolve, suggesting that below $n=2\times10^{18}$ cm^{-3} the unscreened LO phonon interaction dominates the electron energy relaxation process.

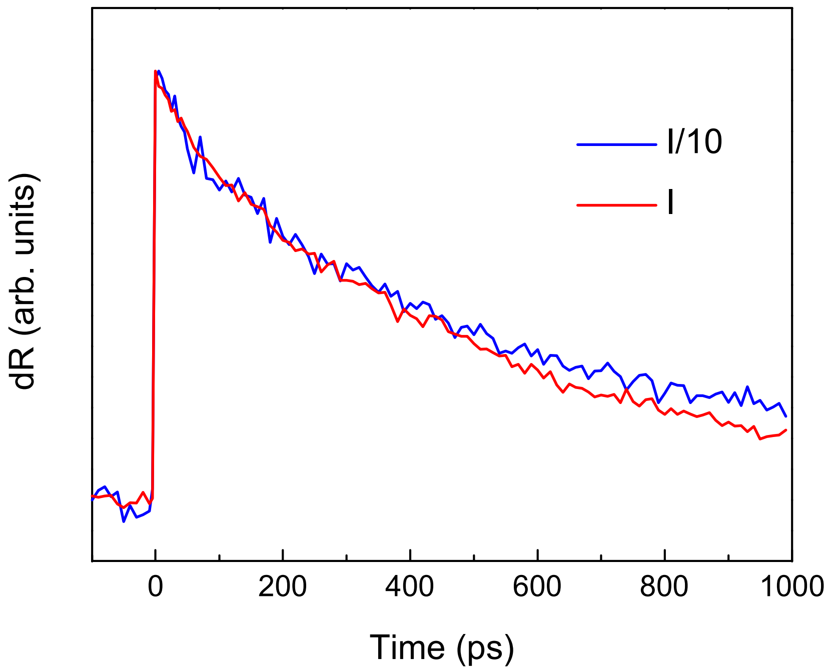


Solid line: carrier density $n=4\times10^{19}cm^{-3}$; dashed line: $n=4.5\times10^{18}cm^{-3}$.

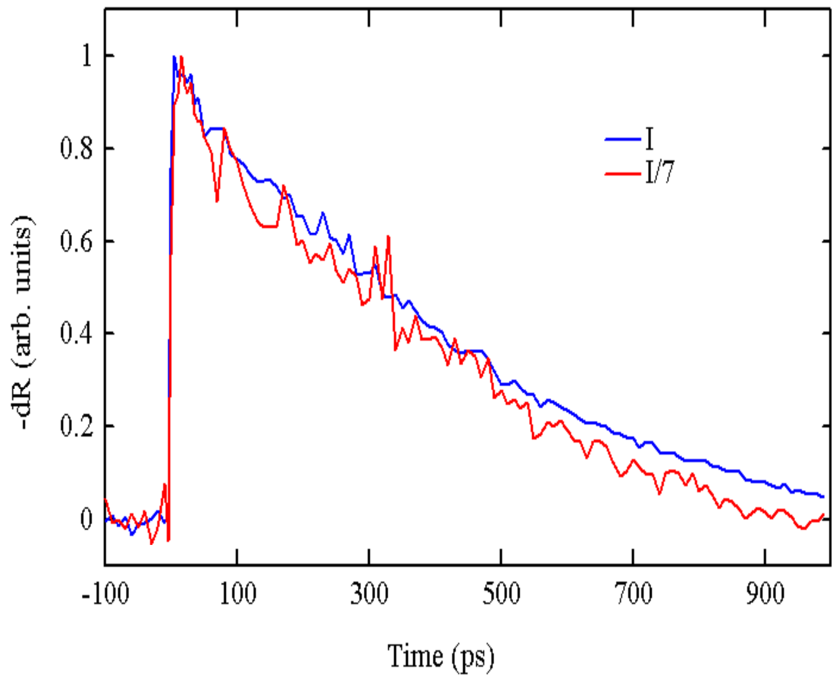
Inset: dashed line: $n=4.5\times10^{18}cm^{-3}$ dotted line: $n=2.2\times10^{18}cm^{-3}$.

Sample provided by R.D. Dupuis, UT-Austin

Comparison of Carrier Lifetimes in LEO and low defect density non-LEO GaN



LEO GaN, 364.5 nm excitation



Non-LEO GaN, 363.4 nm excitation

- The carrier lifetime in low defect density non-LEO GaN approaches that in LEO GaN.

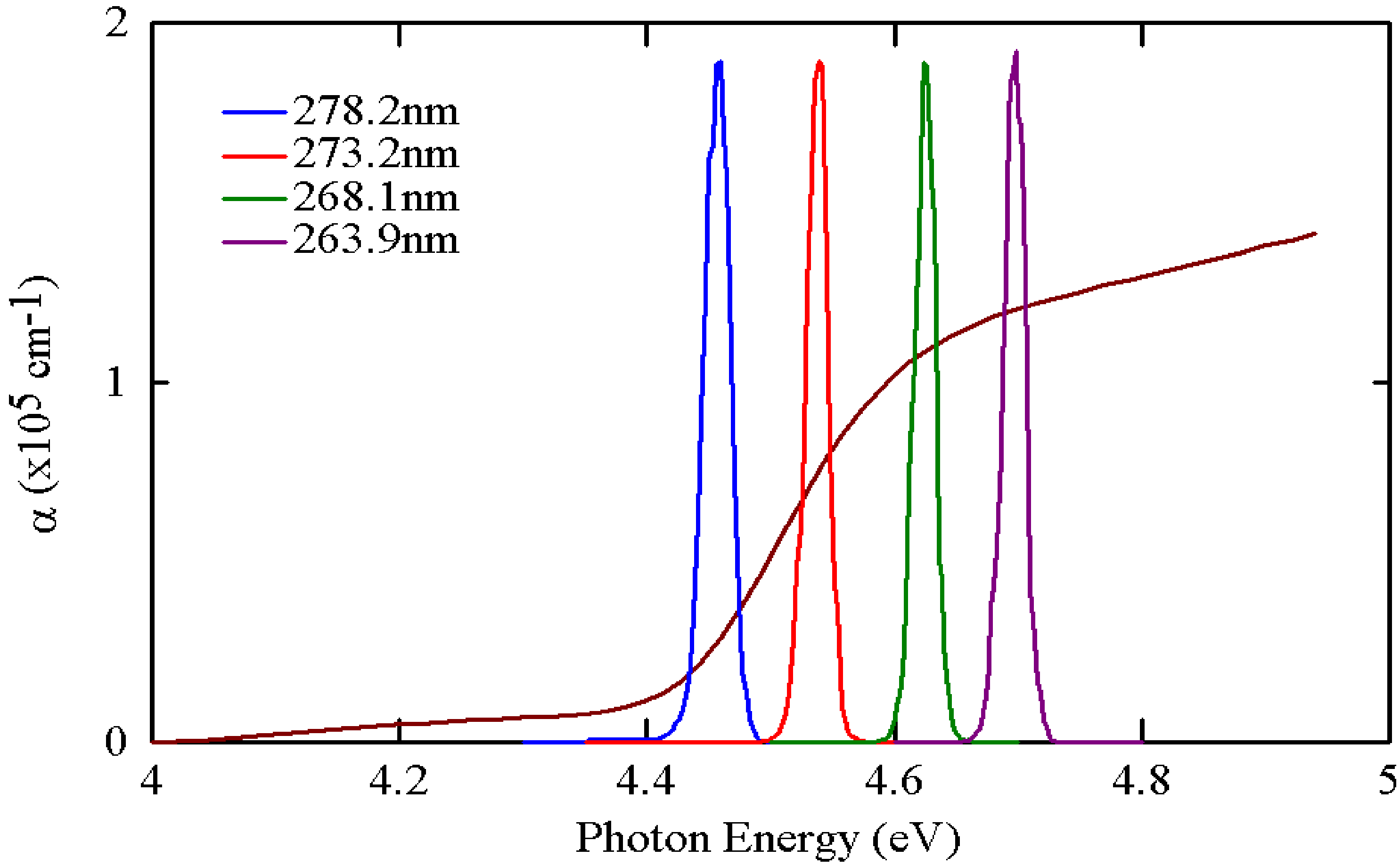
Samples provided by R.D. Dupuis, UT-Austin

Carrier Dynamics in AlGaN

- **Motivation:** Potential fluctuations at the bandedge caused by random alloy fluctuations are strongly correlated to the energy-gap difference between AlN (6.2 eV) and GaN (3.4 eV). Strong localization effects are expected for such a large difference, and ultrafast trapping dynamics should be important.

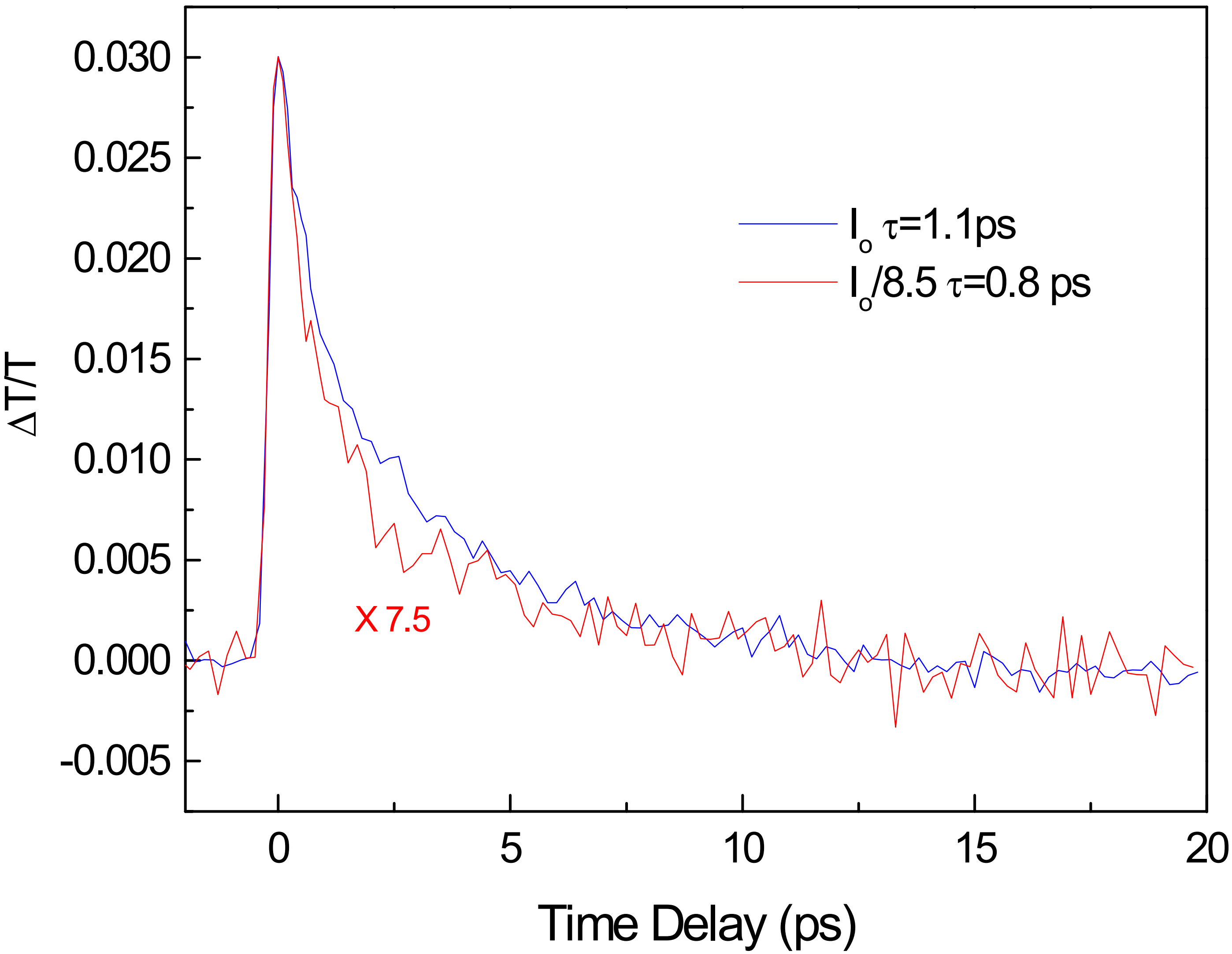
- **Background:** Temperature dependent CW PL and low temperature TRPL show that activation energy and trap-related PL lifetime increase with Al content.

Absorption and Laser Spectra for High Al (~0.4) content

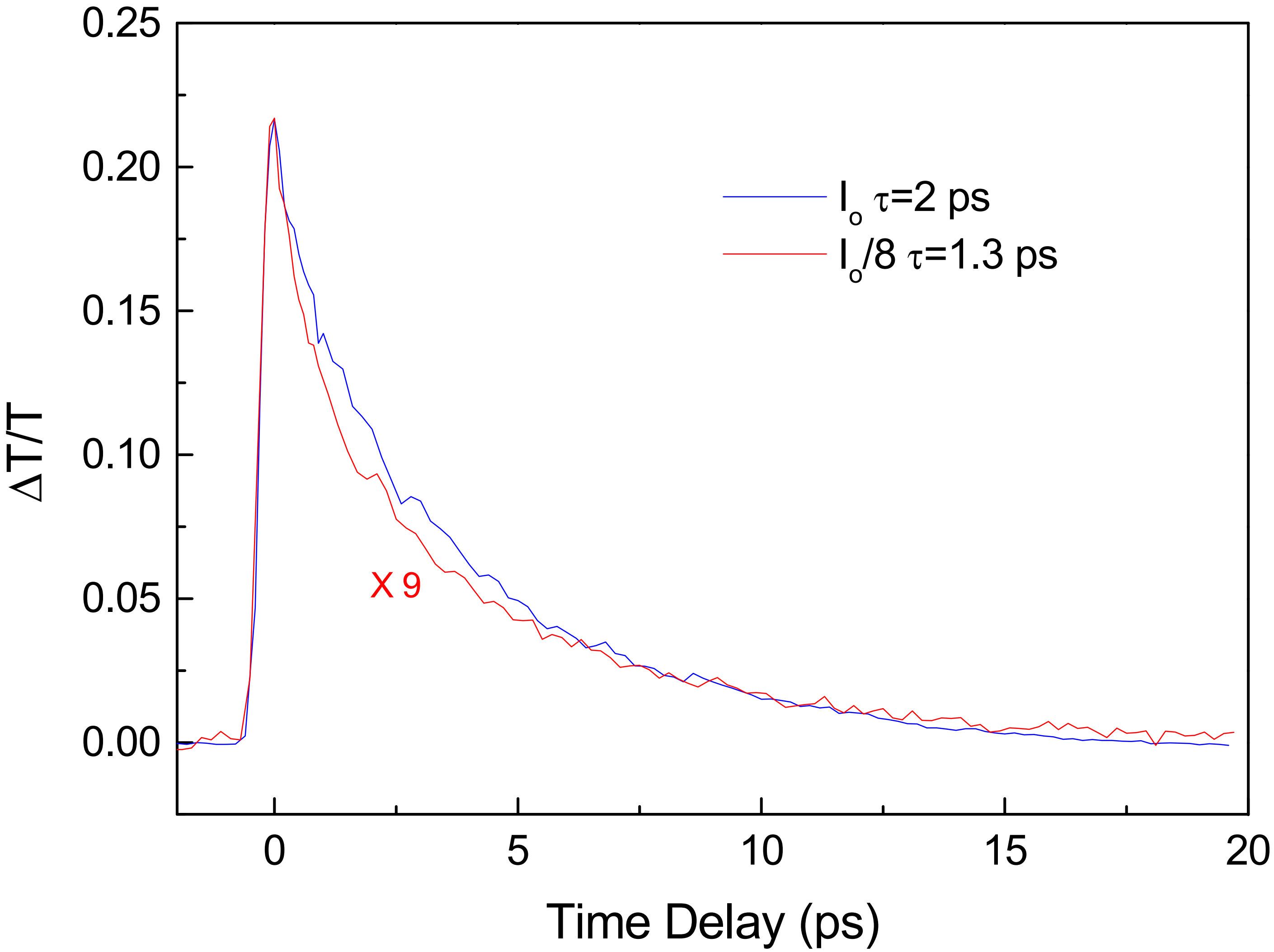


Samples provided by M. Razeghi, Northwestern University

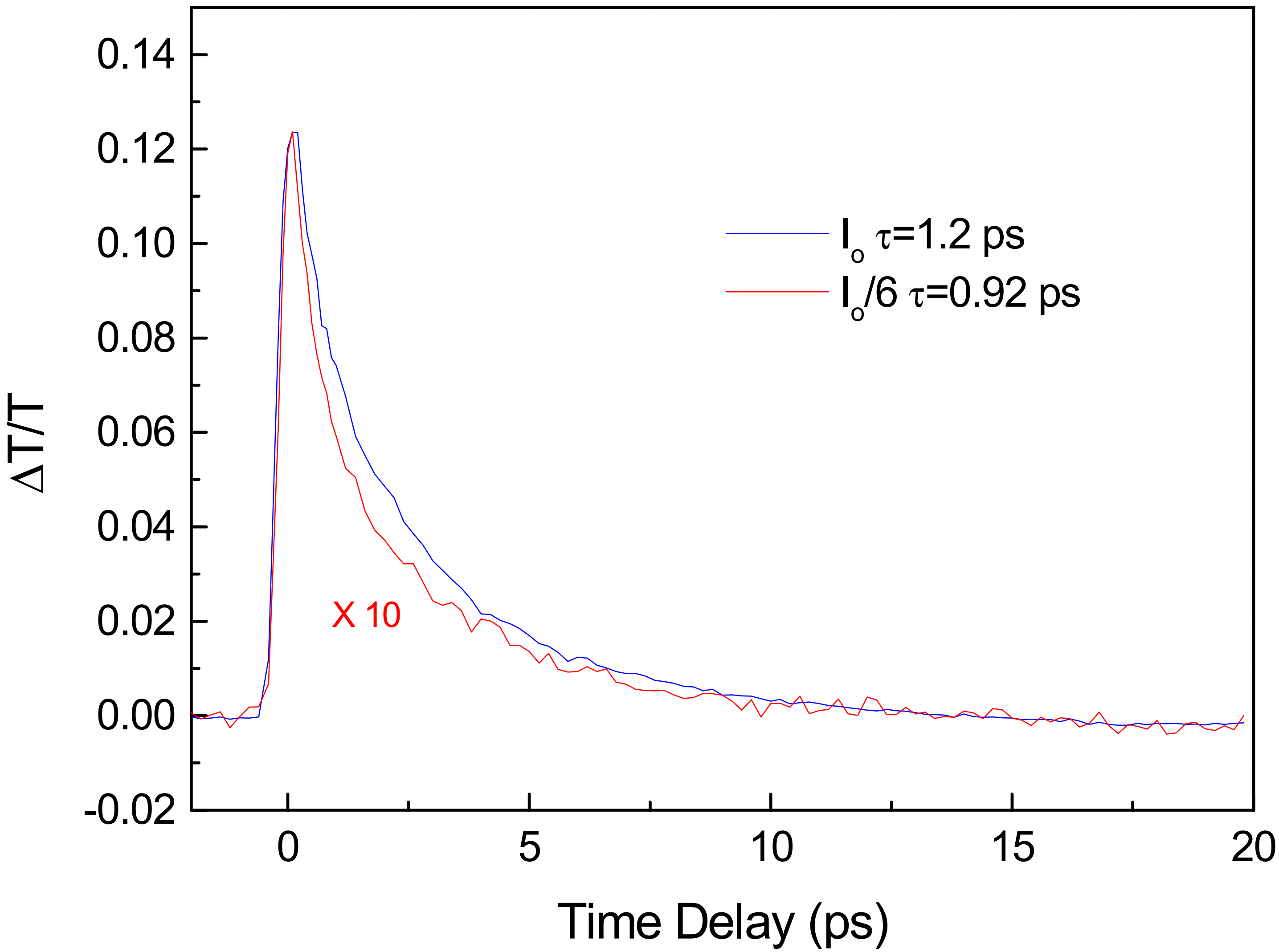
278.2 nm (4.46 eV) data



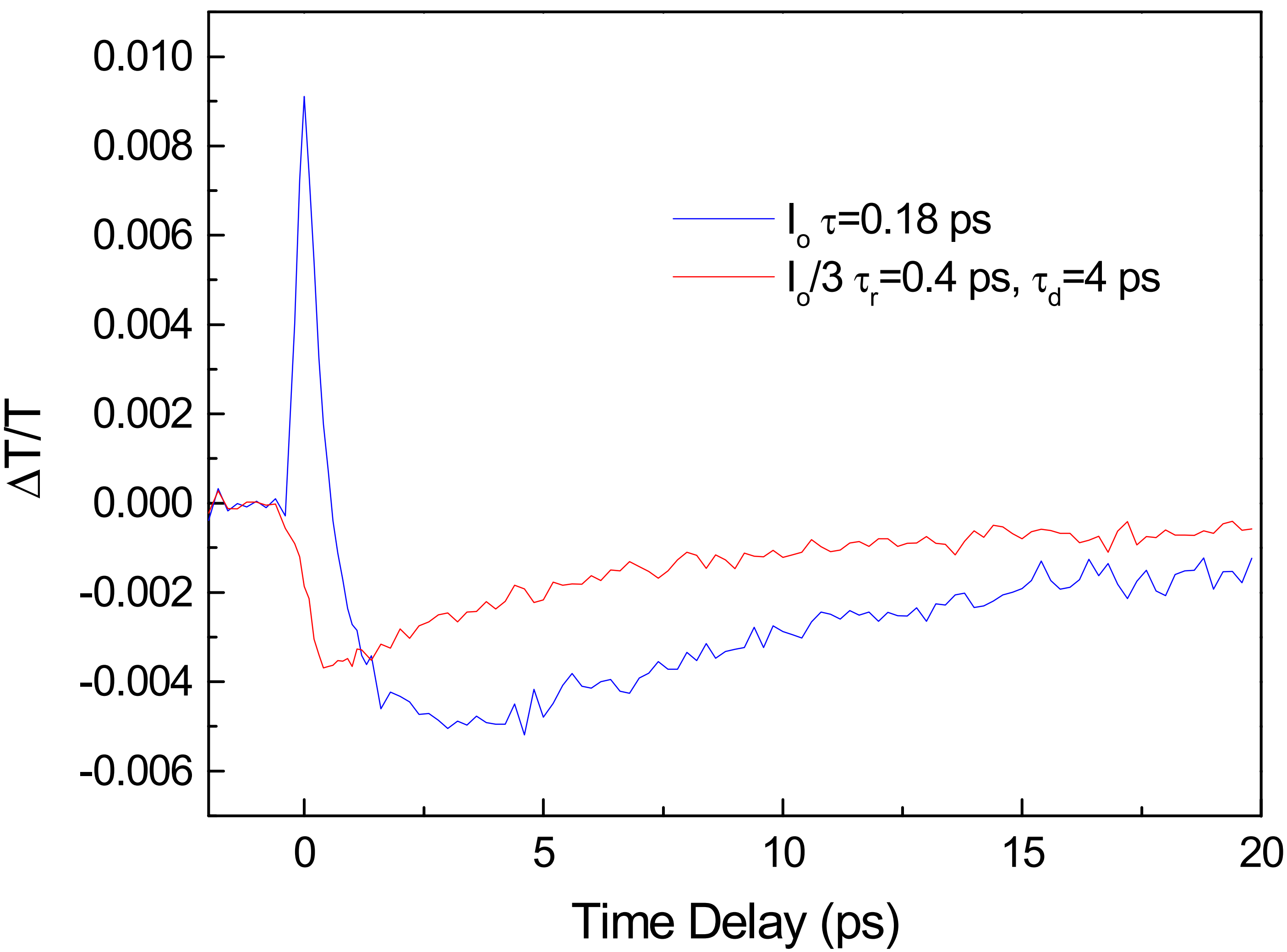
273.2 nm (4.54 eV) data



268.1 nm (4.625 eV) data



263.9 nm (4.7 eV) data



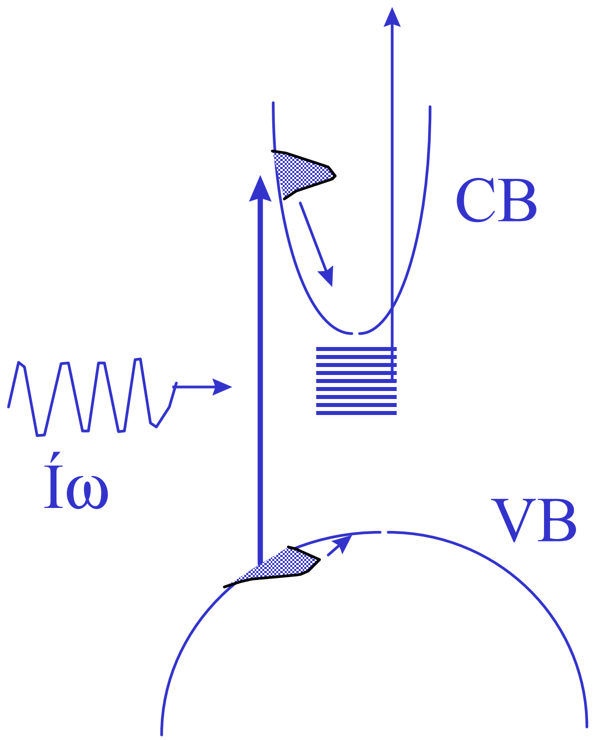
Discussion

For 278.2 nm: bandtail excitation, bleaching decays becoming faster with decreasing intensity suggests trapping in deeper levels.

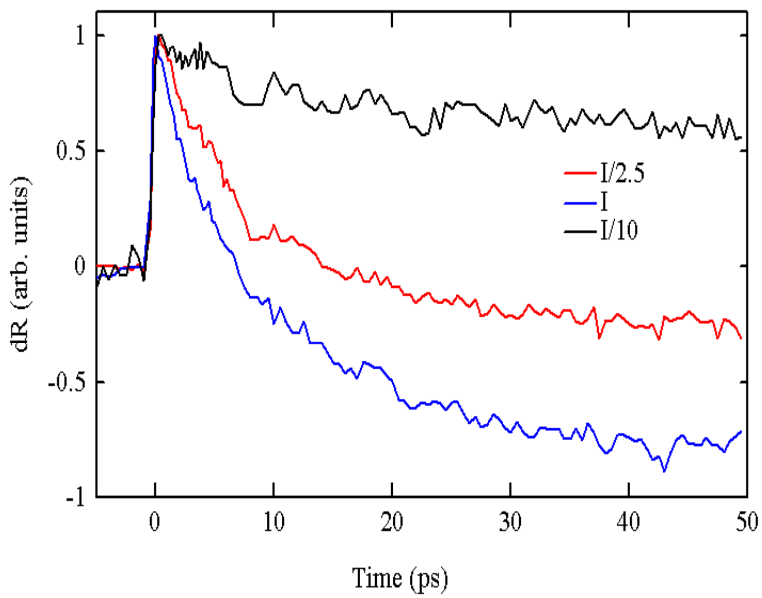
For 273.2 nm: stronger bleaching and slower decays indicative of near-bandedge excitation.

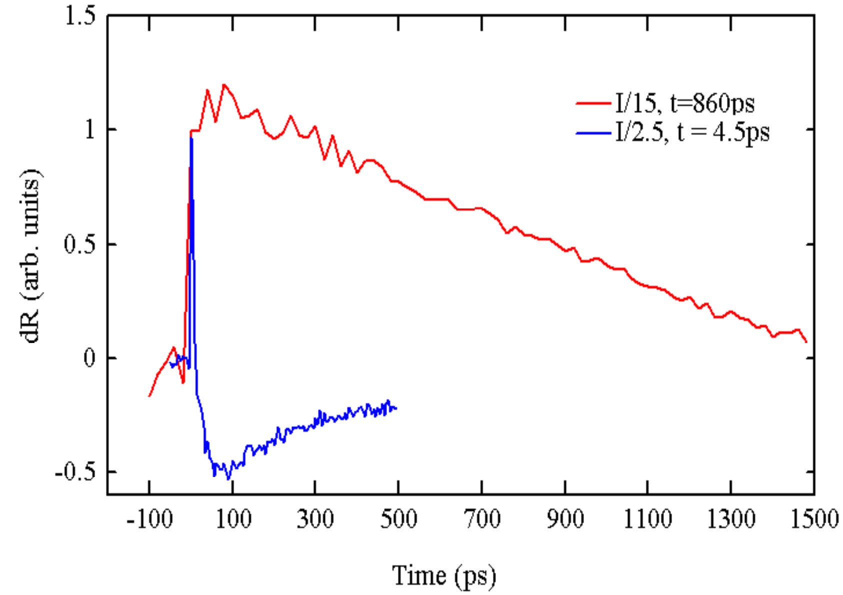
For 268.1 nm: faster decays than previous case suggest the onset of more relaxation channels (e-phonon, e-h scattering).

For 263.9 nm: much weaker, faster bleaching decays suggest e-LO phonon scattering becomes dominant; onset of induced absorption implies excitation from deep states.



Dependence of Localization on Al Content by Time-Resolved Reflectivity

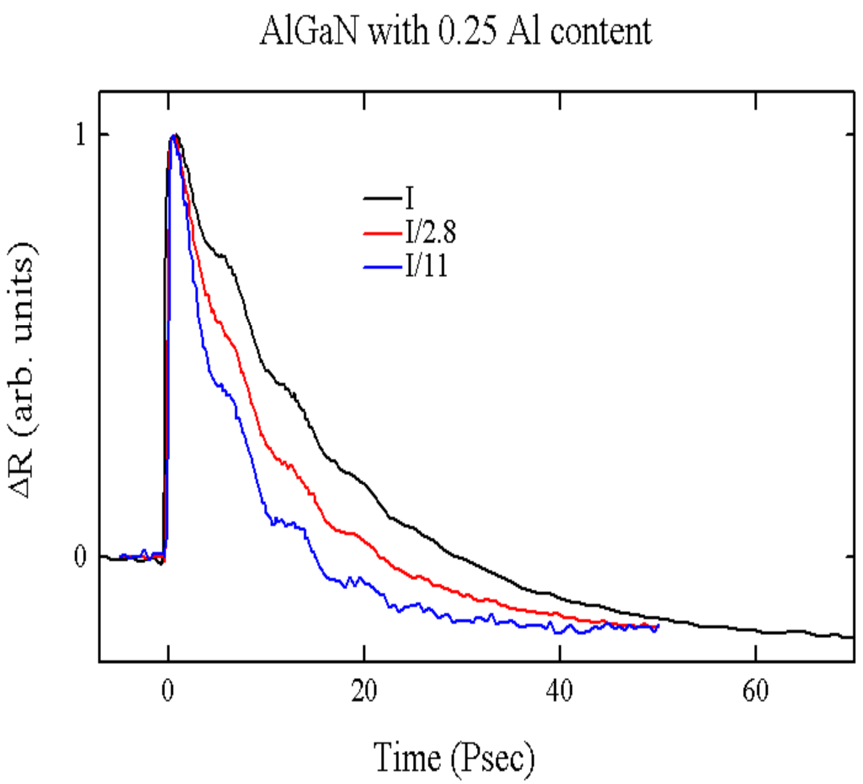


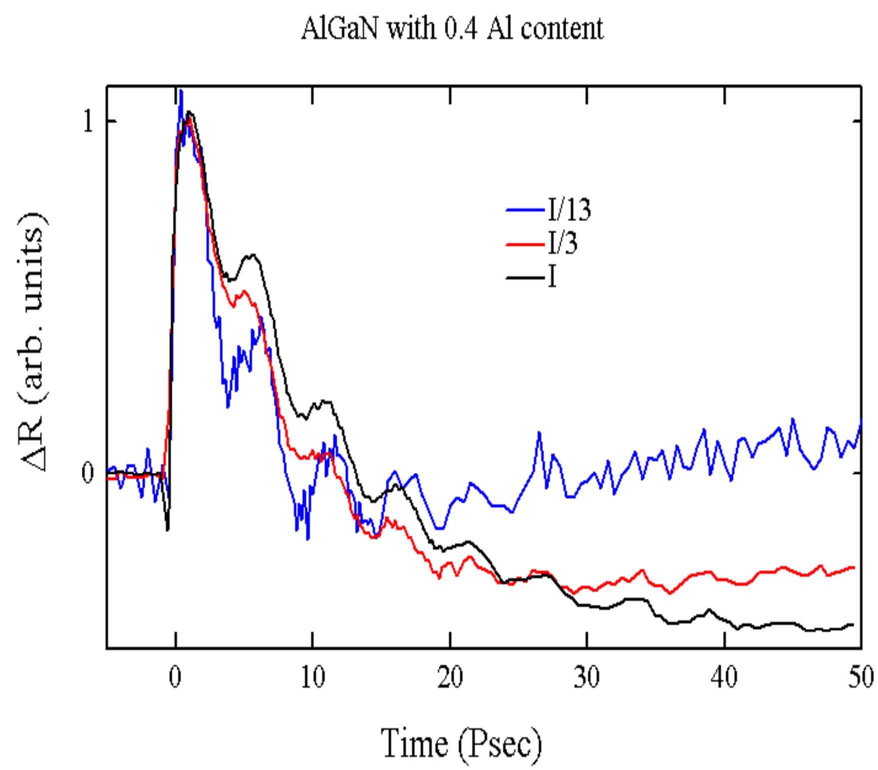


316 nm excitation of AlGaN with 16% Al content (E_g at ~ 322 nm). The fast decays at high intensity suggest ultrafast nonradiative recombination in conjunction with trap saturation. At low intensity the lifetime in the localized states is long (~860 ps). Thus, localization plays a role even for low Al content, although the trapping effects at all densities seem to be more important at higher Al content.

Samples provided by J.F. Schetzina, NC State University

Higher Al Content





- At higher Al content, the ΔR decays become faster with decreasing intensity - localization effects dominate
- The ΔR decays are faster at a given intensity for higher Al content - traps become deeper and more numerous for higher Al content

Samples provided by R.D. Dupuis, UT-Austin

Summary

Femtosecond nonlinear optical techniques using tunable ultraviolet pulses:

- are powerful tools in the study of carrier relaxation and transport in wide bandgap semiconductor materials and devices

- provide information about nonequilibrium processes occurring on ultrafast time scales that cannot be obtained by more conventional techniques.