Light polarization control by H-assisted strain modulation in GaAsN/GaAs heterostructures

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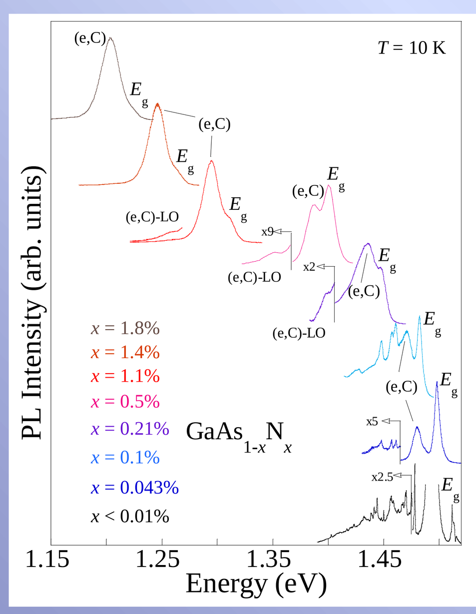
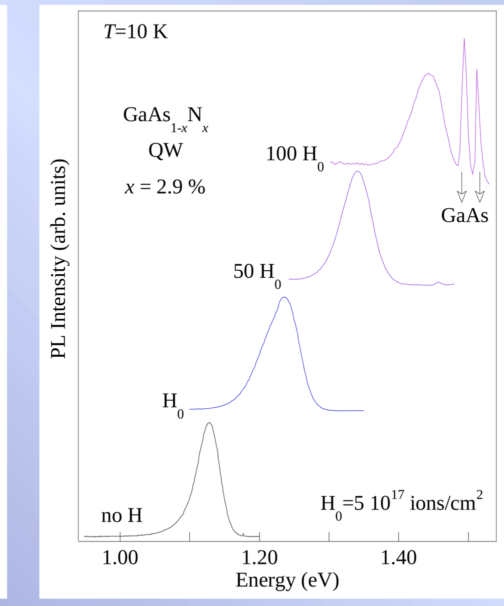
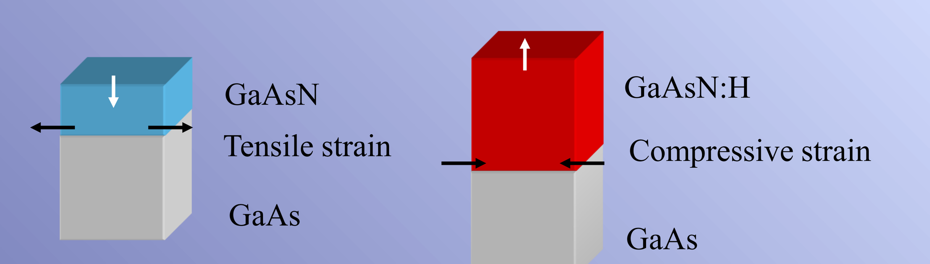
Background

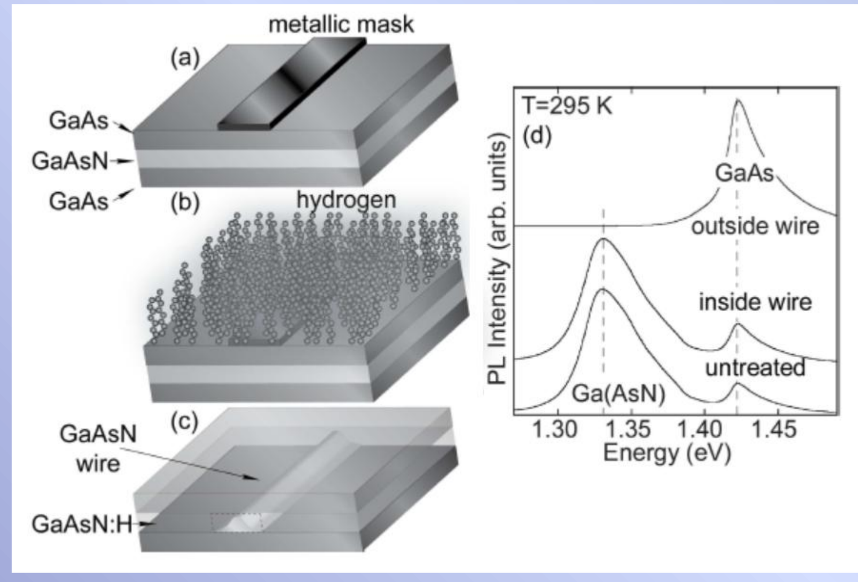




- Incorporation of small percentages (0.1% - 5%) of N impurities in GaAs leads to a large decrease in the bandgap energy [1]
- Hydrogen irradiation leads to the formation of stable N-2H-H complexes [2] with an ensuing full restoration of all electronic and structural properties of the N-free material [3]
- The presence of a third H atom in the complex leads to an expansion of the lattice parameter of GaAsN:H and to a strain reversal, from tensile to compressive [2]



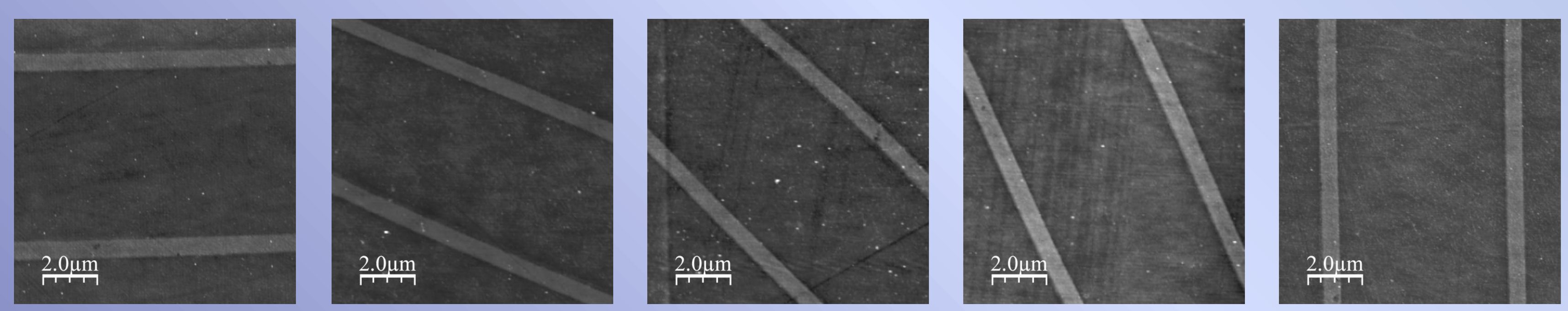
In-Plane bandgap and strain engineering



- Deposition by electron beam lithography of a H-opaque Ti mask on a GaAsN/GaAs heterostructure
- Hydrogen irradiation by a low energy Kaufman source (100 eV H^+ ions)
- Ti mask removal by etching with a HF solution

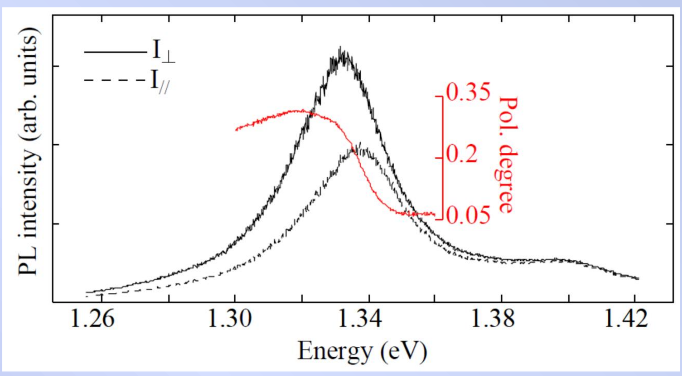
Spatial modulation of bandgap energy and strain fields in the growth plane [4]

Our sample

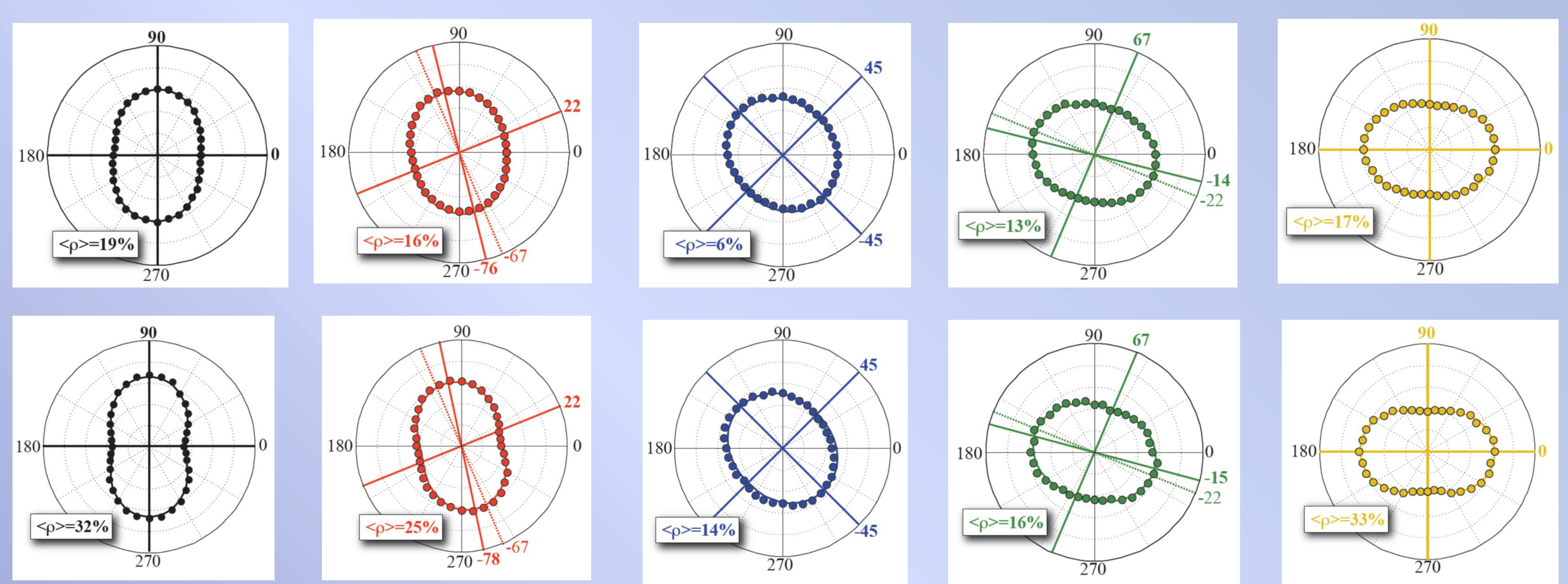


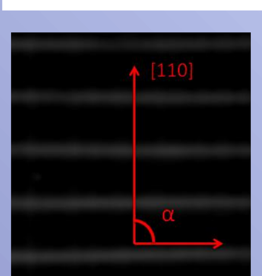
The (001) surface of a $GaAs_{1-x}N_x$/GaAs heterostructure (x=0.8%) was patterned with Ti wires (width w=500 nm) oriented at different angles (0°, 22.5°, 45°, 67.5° and 90°) with respect to the [110] crystallographic direction

Polarization-resolved micro-photoluminescence (PL) spectroscopy



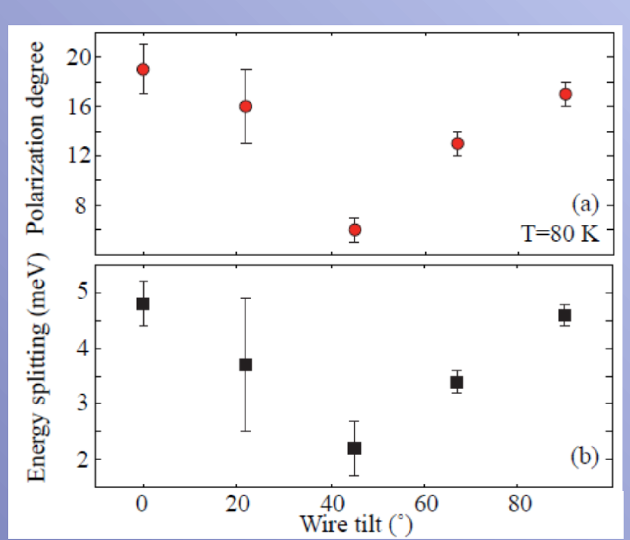
- Strong dependence of the PL intensity of single wires on the light polarization direction
- Energy splitting between the two polarizations

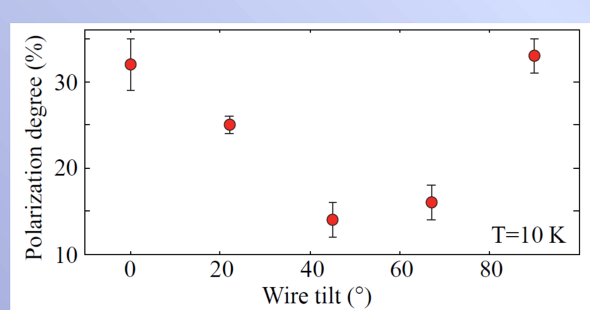




Polarization angle rotates with wire orientation: Light is polarized mainly in the direction perpendicular to the wires, as a consequence of different optical selection rules for the two polarizations

$$I_{\parallel,\perp} \propto \left(\mu_1^{3/2} M_1^{\parallel,\perp} + \mu_2^{3/2} M_2^{\parallel,\perp} e^{-\Delta E_{12}/K_B T}\right)$$

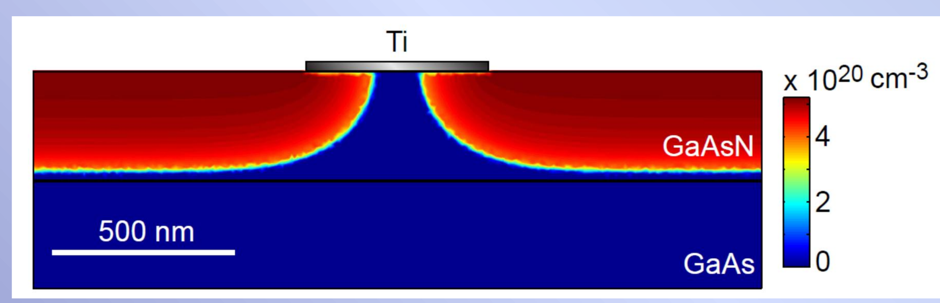




$$\rho = \frac{I_\perp - I_\parallel}{I_\perp + I_\parallel}$$

- ❖ Polarization degree and energy splitting are maximum for wires oriented at 0° and 90°, minimum for wires oriented at 45°
- ❖ A same trend is observed at T=10K and T=80K, except for a polarization degree higher at low T

Finite element calculations



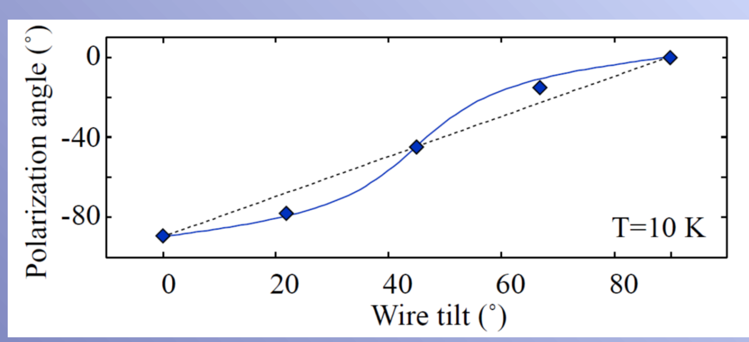
Connection between polarization degree and strain:
Pikus-Bir Hamiltonian

$$H_c(\vec{k}=0) = E_g - |a_c|(\varepsilon_{xx}+\varepsilon_{yy}+\varepsilon_{zz})$$

A simulation of hydrogen diffusion profile is required for a realistic estimate of the system geometry: Starting point for strain tensor calculations

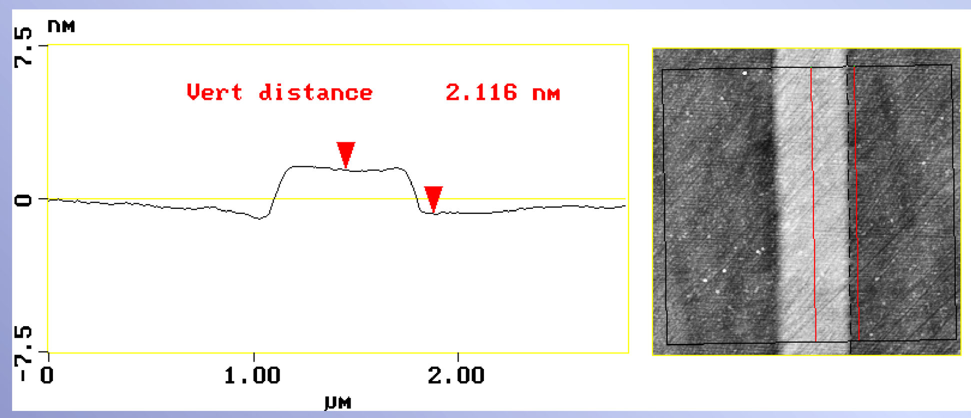
$$H_v(\vec{k}=0) = -\begin{pmatrix} P+Q & -S & R & 0 \\ -S^+ & P-Q & 0 & R \\ R^+ & 0 & P-Q & S \\ 0 & R^+ & S^+ & P+Q \end{pmatrix}$$

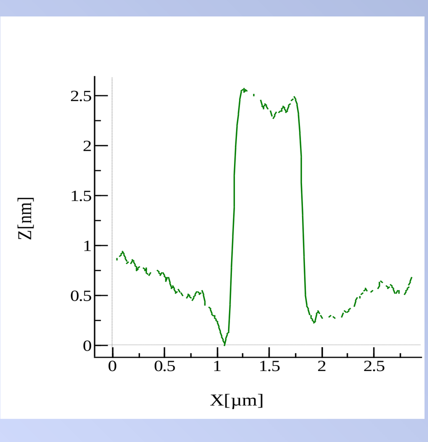
$$P = -|a_v|(\varepsilon_{xx}+\varepsilon_{yy}+\varepsilon_{zz})$$
$$Q = \frac{|b|}{2}(\varepsilon_{xx}+\varepsilon_{yy}-2\varepsilon_{zz})$$
$$R = -\frac{|d|}{2}(\varepsilon_{xx}-\varepsilon_{yy}) + i\sqrt{3}|b|\varepsilon_{xy}$$
$$S = |d|(\varepsilon_{xz}-i\varepsilon_{yz})$$



Good agreeement with experimental results for polarization angle vs wire orientation

Atomic force microscopy (AFM)





The topography map shows a protrusion of about 2 nm of GaAsN wires above hydrogenated barriers, which is due to strain modulation
➡ possible applications for X-ray optical elements based on the Berry-phase effect [5]. However, a different etching of GaAsN and GaAsN:H during Ti removal may play a role (to be verified yet…)

Conclusions

- Spatially controlled hydrogenation of GaAsN shows that the physical properties (bandgap energy and strain fields) of dilute nitrides can be modulated in their growth plane
- Remarkable degree of polarization for light emitted from single GaAsN wires
- Polarization angle strongly dependes on wire orientation with respect to the [110] direction
- Atomic force microscopy reveals a protrusion of GaAsN wires above hydrogenated barriers
- High potential for light polarization control in semiconductor optical devices and for realization of X-ray optical elements

References

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