A comprehensive Study of InGaAs/InP Materials via High Resolution Electron Microscopy Technology

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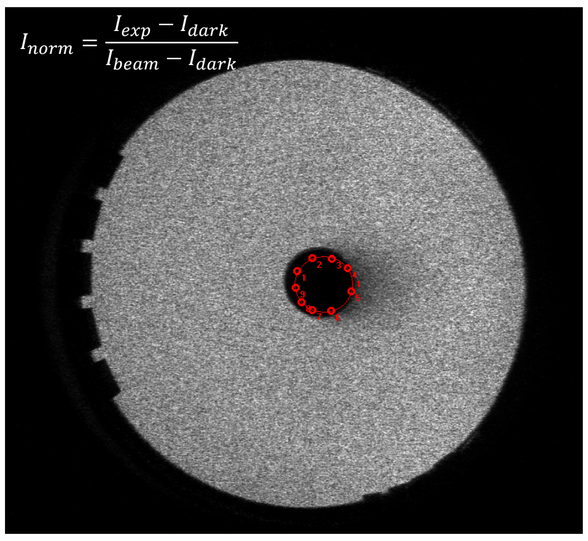
Introduction

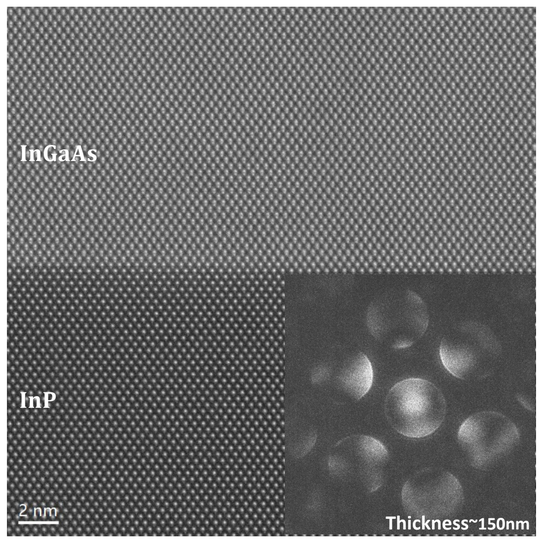
InGaAs/InP is usually used to fabricating valanche phosphide (InP) APDs in near-infrared band, having a wide range of applications in the fields of quantum-secure communication and light detection. Materials nanostructures detection plays a key role in analyzing the properties of materials and interpreting the performance of fabricated devices. In this work, the characterization of InGaAs/InP is achieved through the combination of electron microscopy tools high-angle annular dark-field (HAADF) STEM images, electron energy loss spectroscopy (EELS) and electron hologram. STEM-HAADF images intensity have a strong Z-contrast dependent, showing a powerful potential for localized nanoscale structures composition analysis. The valance EELS spectrum in low-loss region can provide localized information to disentangle electronic properties through the analysis of the spectral features with deriving dielectric response from the energy loss function. Electrostatic potential variations across the junctions can be interpreted from electron hologram, which is an interferometric method providing quantitative access to phase shifts experienced by the incident electron wave front due to interactions with the electrostatic potentials of the sample.

Quantitative STEM method for composition measurement

Experimental results

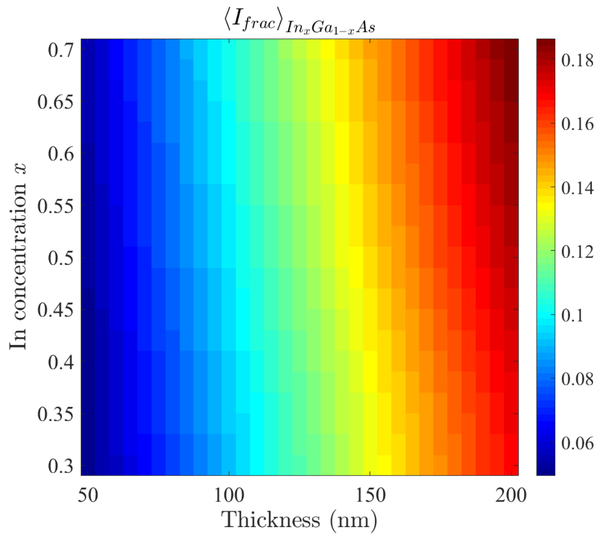


● HAADF detector image

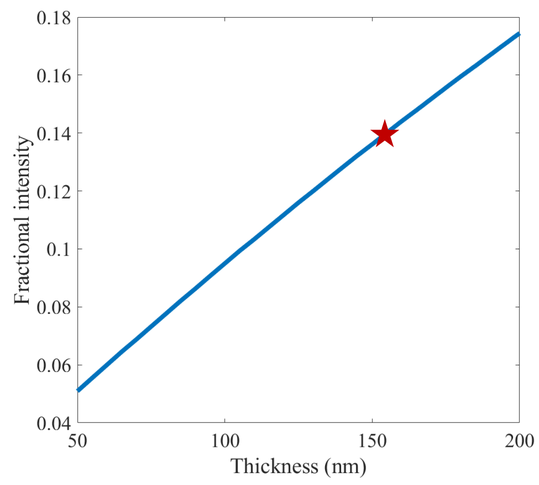


● HAADF-STEM intensity image

Simulated results



● Simulated mapping as a function of composition and thickness

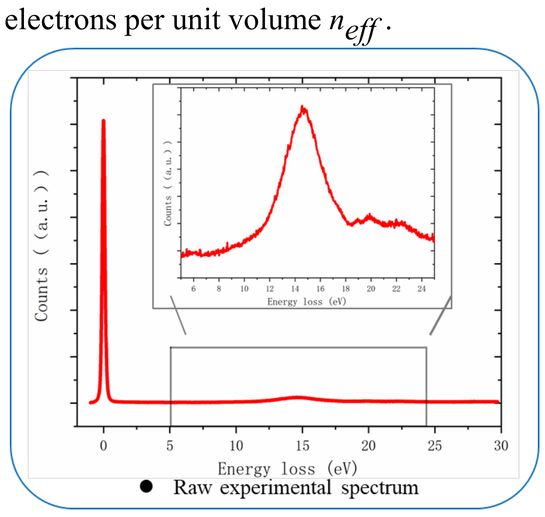


● InP Simulated results as a function of thickness

STEM-HAADF image intensity is also influenced by sample thickness and crystal orientation, as well as the microscope optical parameters. A comprehensive quantification of elemental composition is provided after the comparison between normalized intensity image and standard simulation results. A parameter I_{norm} is defined for normalizing an experimental STEM image, it is usually subdivided into unit cell in which the intensity is averaged. the incident beam I_{beam} was determined by changing the operation mode to imaging mode and scanning across the HAADF detector in vacuum region. Background signal I_{dark} can be recorded in vacuum region. After background subtraction, the normalization was carried out according to the equation. Multislice algorithm [1] incooperated with frozen phonon model was applied to construct a simulated matrix mapping as a function of composition and thickness. The variation of doped atomic components was obtained by comparing the experimental results with the simulated database. The simulated ternary compound database is a function of thickness and composition. In order to obtain the composition information, the sample thickness is considered to be uniform in the local range of the interface. The sample thickness of the binary compound is determined by InP quantitative simulation results and CBED pattern, and then the elements of the ternary compound sample were analyzed.

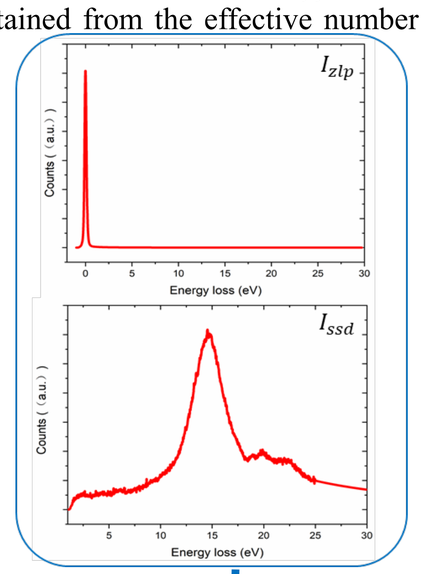
Valence EELS spectrum for electron effective mass determination

The effective electron mass, which is related to the mobility of charge carriers as well as the density of states, can be deduced from VEELS spectra[2]. This analysis is based on the relation between plasmon energy E_p, the electron concentration associated with the valence plasmon, n, and the high frequency dielectric constant, ε_∞. A Fourier-log algorithm is used to do a deconvolution towards raw experimental spectrum to get zero loss spectrum I_{zlp} and single scattering distribution I_{ssd}. Then a Kramers-Kronig transform involving the Cerenkov effects was performed to get the real ε_1 and imaginary ε_2 parts of the dielectric function. ε_∞ is obtained by taking the values of $\varepsilon_{0,neff}$ at energy losses greater than the valence band transitions, while n is obtained from the effective number of electrons per unit volume n_{eff}.

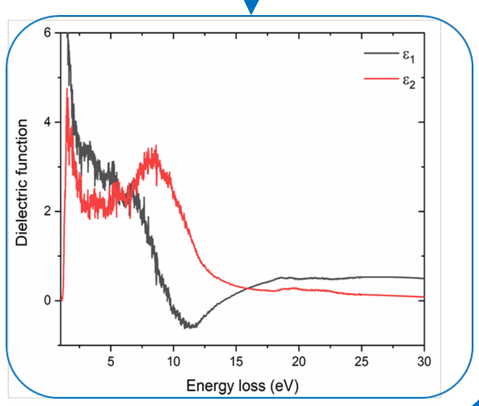


● Raw experimental spectrum

Deconvolution



Kramers-kronig transform

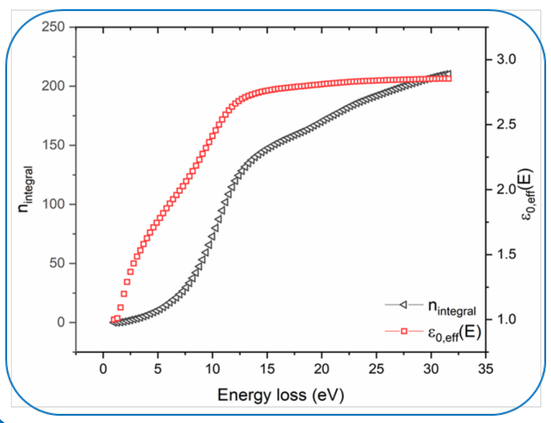


Dielectric function tools

$$n_{eff}(\varepsilon_2) = \frac{2\varepsilon_0 m_0}{\pi h^2 e^2} \int_0^\infty E' \varepsilon_2(E') dE'$$

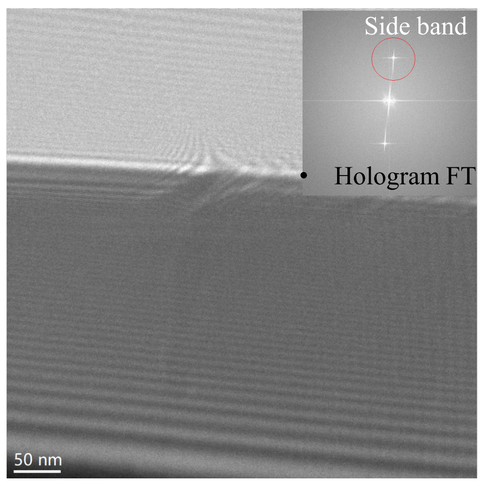
$$\varepsilon_{0,eff}(E) = 1 + \frac{2}{\pi} \int_0^{E_0} \frac{\varepsilon_2(E)}{E} dE$$

$$m_e^* = \frac{n\, e^2}{\omega_p^2 \varepsilon_0 \varepsilon_\infty}$$

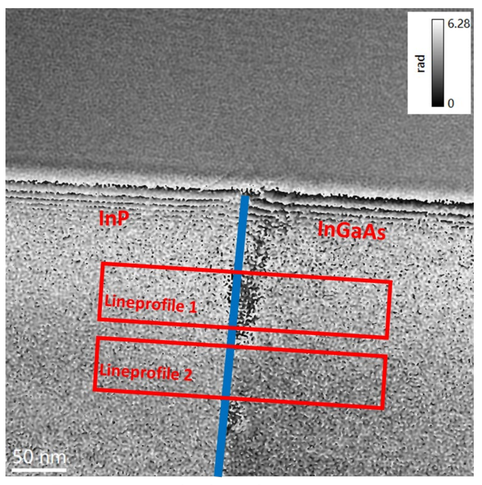


Electron holography for heterojunctions potential difference

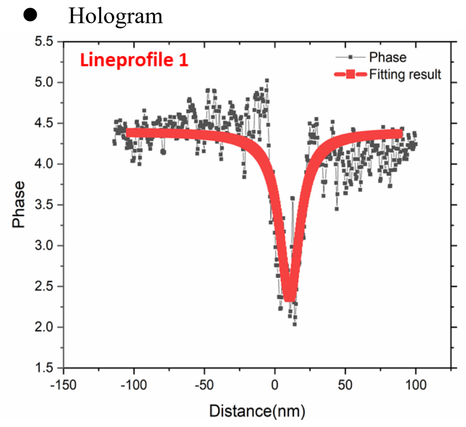
The electrostatic potentials can be expressed as a phase difference of electron waves as shown in the equation. This sample thickness t is uniform at the interface, mean electrostatic potentials difference can be expressed as a phase difference of electron waves by detecting the phase distribution from hologram.

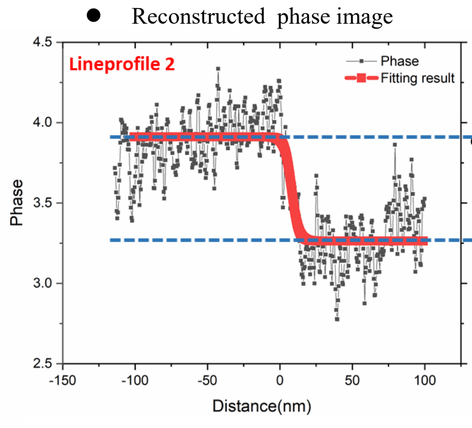


● Hologram



● Reconstructed phase image





$$\Delta\varphi = C_E V \Delta t\,,\ \Delta\varphi = \varphi_1 - \varphi_2$$

Reference:

[1] Advanced Computing in Electron Microscopy, E. J. Kirkland, Springer, 2nd ed. (2010)

[2] Infrared Physics, B. Elizabeth, 17:111-119 (1977)