Quantitative High-Resolution TEM/STEM and Diffraction

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Electron holography for characterization of semiconductor structures down to the atomic scale

M. Lehmann[1], F. Genz[1], U. Hömpler[1], F. Kießling[1], T. Niermann[1], J.B. Park[1]

[1]TU Berlin, Institut für Optik und Atomare Physik, Berlin, Germany

Lehmann@physik.tu-berlin.de

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Transmission electron microscopy (TEM) is an indispensable method for characterization of semiconductor structures down to the atomic scale. However, solid state physicists and engineers, who grow these increasingly complicated structures on a shrinking scale, do not only have scientific questions, which can be solved just by imaging these structures on the nanometer scale by conventional TEM; there is an increasing demand also for measurements of electric potentials and strain fields, since they mainly determine most macroscopic properties of corresponding devices. Furthermore, structural questions comprising also compositional measurements down to the atomic scale are supposed to be solved by means of HRTEM. Last but not least, error bars for the measured values have to be given. These scientific questions, which are to be answered by TEM, have to be considered within the framework of wave optics. Conventional TEM, however, only records the intensity of the electron wave, whereas the phase information is lost. In particular, this forbids from a single micrograph on the nanometer scale the measurement of electric potentials or on the atomic scale the a-posteriori correction of residual aberrations even necessary for a Cs-corrected TEM, since their accuracy of hardware correction is limited. Off-axis electron holography allows the encoding of amplitude and phase of the electron wave in a single electron hologram. In principle after reconstruction, amplitude and phase of the electron wave is available without transfer gaps down to the information limit of the TEM. Besides the spatial resolution given by the fringe spacing and the information limit of the TEM, the quality of the reconstructed wave in terms of phase resolution is additionally limited by the number of recorded electrons and by the interference fringe contrast. Furthermore, artifacts like Fresnel diffraction at the biprism filament reduce the quality of the reconstructed wave. Careful analysis of all these factors shows that a dedicated instrument like our FEI Titan Berlin Holography Special TEM may overcome these obstacles: Equipped with a high-brightness gun (XFEG), only using a 2-condenser illumination system is simplifying hologram acquisition [1]. Utilizing two biprisms in different planes drastically reduces the Fresnel diffraction over the field of view [2]. Applying exposure times within the stability limits of the instrument of typically 2 .. 8 s for a single micrograph, a special averaging scheme over a series of holograms compensating for specimen drift, defocus drift, biprism drifts as well as hologram contrast variations allows standard deviations in phase and amplitude of $2\pi/104$ and 0.04, respectively, with a lateral resolution better than 0.1 nm [3]. This is the basis for compositional analysis with atomic resolution.

These high-quality electron holograms now permit tackling serious scientific questions, e.g., from solid state physics of semiconductors. One important application field of electron holography is the imaging of potential differences in p-n junctions. Careful analysis of the phase shift of p-n junctions in GaN shows, however, that the measured phase difference is about a factor of ten less than expected. It turns out that the measured potential difference considerably depends on the electron dose rate applied for recording the hologram. This can partially be related to a beam-induced generation of electron-hole pairs [4]. Additionally, the charging character of the sample strongly depends on the modification of its surface [4] demonstrating the need for a full modeling of the specimen under investigation. An even more complicated structure is a multiquantum well comprising of GaN quantum wells (QW) and $Al_{0.48}Ga_{0.52}N$ barriers (figure 1) (5). Because of experimental uncertainties of specimen thickness variation over the field of view, only the potential ratio between QWs and barriers can be given (figure 2). Here, the measured potential ratio is not only given by the different mean inner potential between QW and barrier, but also by strain and resulting piezoelectric field, which only partially compensates the spontaneous polarization of GaN in [0001] growing direction (figure 2). Furthermore, the modulation within barriers may partly be related to interface charges compensating the charge accumulation exhibiting the piezoelectric fields in the QWs.

Such a dedicated experimental setup does not only allow the recording of "conventional" off-axis electron holograms, where normally the object modulated wave is brought to interference with an unmodulated reference wave, but also the acquisition of dark-field electron holograms, where a strained region of interest is brought to an overlap with an unstrained region as reference utilizing a strain-sensitive reflection by means of the objective aperture [6]. Such an example is a strain analysis of buried AlAs/oxide stressor layers for site-controlled quantum dots (QD) growth important, e.g., for single-photon emitters [7]. In particular, the double biprism setup is beneficial preventing Fresnel diffraction as well as giving extra flexibility in experimental setup in term of spatial resolution and field of view. In summary, recent progress of electron holography and related methods enables now tackling important solid state problems in semiconductor physics.

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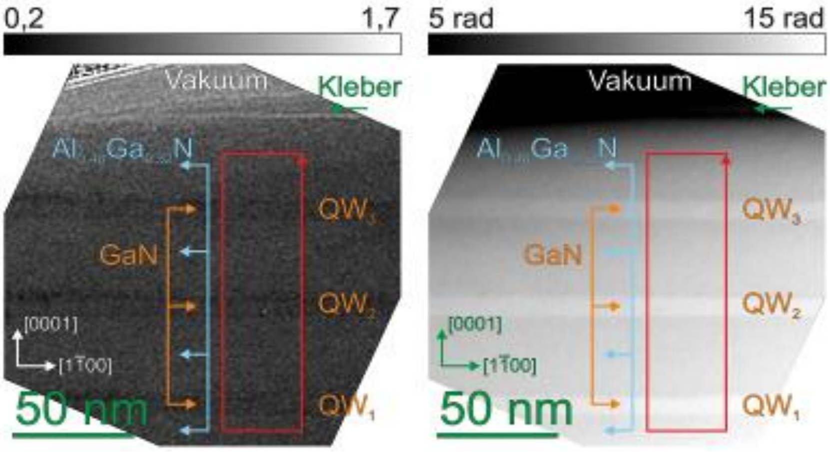

Figure 1. GaN/AlGaN-MQW: Amplitude (left) and phase (right) of the electron wave as reconstructed from the electron hologram. Almost no Fresnel diffraction can be observed over the field of view. The phase image clearly reveals the QWs. However, the sample has a steep thickness gradient preventing a direct interpretation of the phase modulation in term of absolute potential difference between GaN QWs and AlGaN barriers.

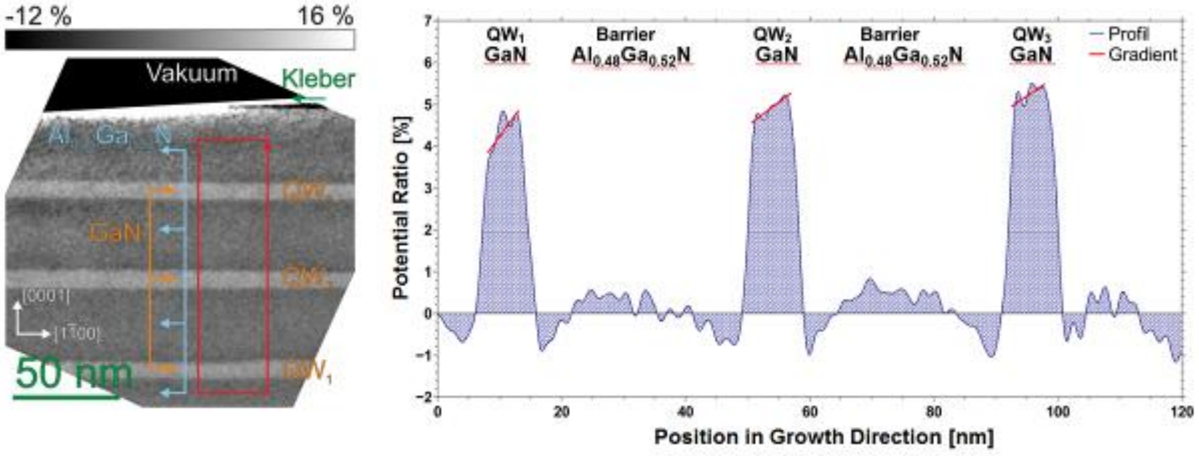

Figure 2. Potential ratio between QWs and barriers of figure 1. The gradient in the QWs can be attributed to piezoelectric fields. Potential modulations in the barriers can have their cause in screening charges compensating interface charges exhibiting the piezoelectric fields in the QWs.