Low Voltage EELS and Bessel Beams in Semiconductor Science

M. Stöger-Pollach[1], T. Schachinger[1], W. Hetaba[1], D. Abou-Ras [2], R. Rodemeier [3]

1. TU Wien, USTEM, Wiedner Hauptstraße 8-10, 1040 Vienna, Austria
2. HZB für Materialien und Energie GmbH, Hahn-Meitner-Platz 1, 14109 Berlin, Germany
3. GATAN GmbH, Ingolstädterstr. 12, 80807 Munich, Germany

E-mail: stoeger@ustem.tuwien.ac.at

Very recently, low voltage electron microscopy has transformed into a state-of-the-art technique for materials science [1]. Although its main area of application can be found in the analysis of 2D materials and beam sensitive structures, it becomes more and more relevant in semiconductor science, too. In the present work we discuss applications on valence electron energy loss spectrometry (VEELS) for studying optical properties and band gap variations and the determination of anisotropy effects in the energy loss near edge structure (ELNES) of Boron Nitride (BN).

For VEELS of semiconductors low beam energies have a unique advantage over high beam energies: the velocity of the swift probe electron can be kept that small, that the Čerenkov effect can be avoided. Thus only transition radiation has to be taken into account when optical properties have to be determined from the probed material. In the present study we demonstrate the measurement of bandgaps of a Cu(In,Ga)Se_2 solar cell, where an In/Ga gradient can be observed within the optically active layer (Fig.1, left). We use a 20keV electron beam and a collection angle of 13mrad for the spatially resolved experiments and find a band gaps in the range of 1.11 eV for $CuIn_{0.82}Ga_{0.18}Se_2$ to 1.55 eV for $CuIn_{0.18}Ga_{0.82}Se_2$ (Fig.1, right).

But for increasing the spatial resolution in electron spectrometry low beam energies are not always an advantage over higher ones. Especially because slower electrons can be focused worse with respect to faster ones and they are more easily deflected by external magnetic fields. Thus small instabilities are the consequence. Additionally the inelastic delocalization is reduced only a little when decreasing the beam energy. We discuss new pathways for circumvent both, the instabilities by using higher beam energies, and the inelastic delocalization by using conical dark-field STEM-VEELS using a Bessel beam. With this new set-up we automatically avoid the collection of electrons having excited Čerenkov photons and improve the spatial resolution of the STEM probe. For the Silicon plasmon loss we gain a delocalization of 5.9Å (instead of 20Å being measured under conventional STEM conditions).

The ELNES of anisotropic semiconductors can be studied when varying the ratio between the transferred momenta being parallel and perpendicular to the beam axes. This variation can be either achieved by varying the collection semi angle, by shifting the collection aperture in the reciprocal space or by simply varying the energy of the electron probe. In the present study we employ the latter method on BN (Figs. 2 and 3). We vary the beam energy in the range from 200 keV to 20 keV and compare the results with simulations using the Wien2K software (Fig. 4).

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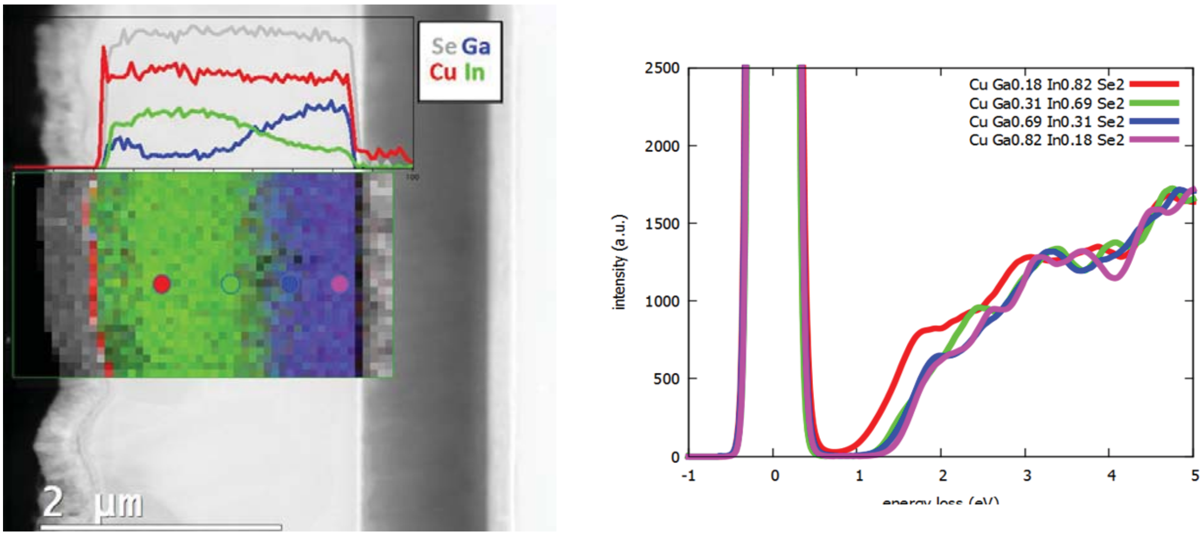

Fig. 1. Left: EDX map and profile across the CIGS-layer. The coloured circles mark the positions for the corresponding VEELS measurements. Right: VEELS measurements showing shifts in the bandgap depending on the chemical composition determined by EDX.

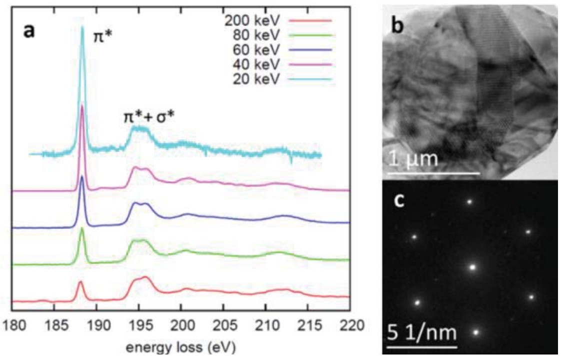

Fig. 2. a) Boron-K edge of BN recorded with various incident beam energies (normalized to the 195.8 eV peak). b) Bright field image of the BN specimen. c) Diffraction pattern of h-BN showing the [0001]-orientation. Consequently the c-axes of the h-BN is parallel to the beam axes.

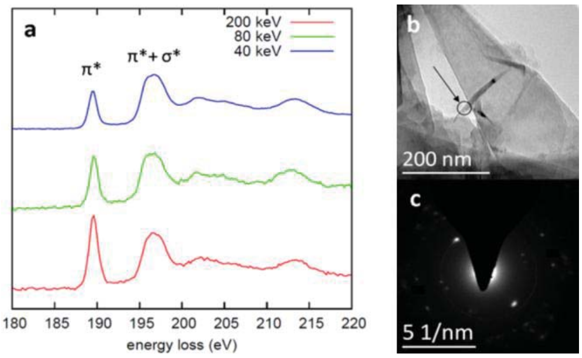

Fig. 3. a) Boron-K edge of BN recorded with various incident beam energies (normalized to the 195.8 eV peak). b) Bright field image of the BN specimen. The circle indicates the position of the EELS experiments. c) Diffraction pattern of h-BN showing the (0002) spots only. Consequently the c-axes of the h-BN is perpendicular to the beam axes.

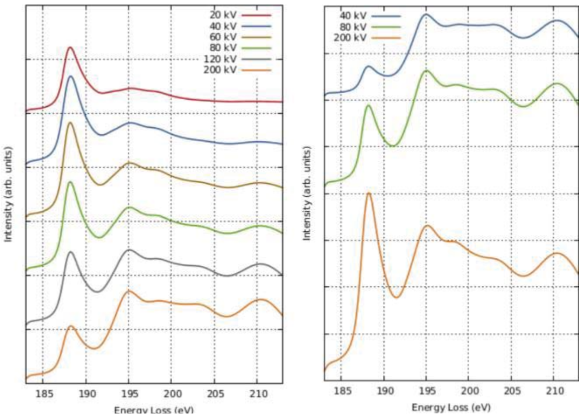

Fig. 4. Left: Boron-K edge of BN [0001]. Consequently the c-axes of the h-BN is parallel to the beam axes. Right: Boron-K edge of BN [0110]. Consequently the c-axes of the h-BN is perpendicular to the beam axes.