

## Investigating the potential variation of in-operando semiconductor nanostructures in electron beam direction

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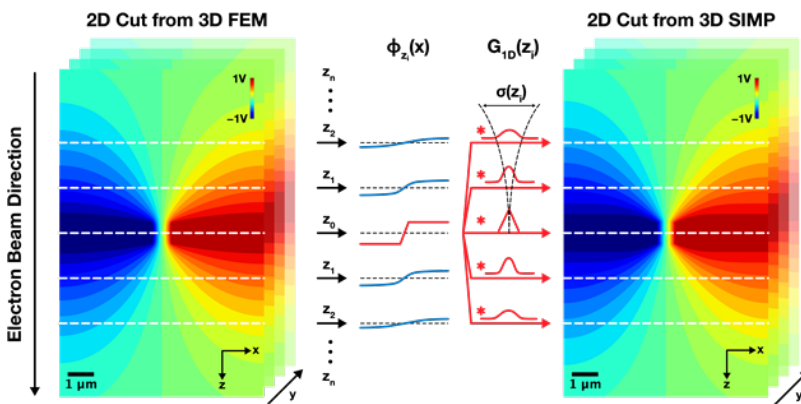
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Off-axis electron holography is a well-established method for the investigation of projected potential distributions down to atomic spatial resolution. However, in the case of in-operando (electrical biasing) investigations of externally controlled semiconductor nanostructures, parasitic modulations of the electron wave occur due to long-range electrostatic stray fields [1]. In addition, a well-known problem is the alteration of the sample during preparation using a focused ion beam (e.g. ion implantation, surface amorphization or generation of conducting surfaces), which also severely influences the potential distribution within the sample [2]. Both effects have a particular impact in the direction of the electron beam as well, which makes a quantitative analysis particularly difficult. Standard approaches to resolve the entire potential distribution involve projective tilt series and their tomographic reconstruction [3], which entail a significant measurement effort (e.g. sample tracking or long-time stability) and instrumental limitations (e.g. limited tilt angle (i.e. missing wedge), interior Radon transform or parallax displacement), in addition to extensive simulations (e.g. FEM or DEM), which are highly computationally intensive and require rarely given knowledge of the microscopic charge carrier distribution.

Here, a simple and intuitive model (SIMP) for the approximation of such potential distributions inside and outside nanostructured FIB-prepared samples of a p-n junction, requiring a limited set of parameters, is presented. The model uses only independent convolutions of an initial potential distribution (e.g. analytic textbook models) with a Gaussian kernel (see attached figure), allowing the reconstruction of the entire potential distribution from only one measured projection (electron hologram). In addition, various contacted semiconductor nanostructure samples (TEM-lamellae) are produced in a systematic approach using FIB under varying preparation parameters (i.e. currents and acceleration voltages of the ions) to evaluate the proposed model.

In comparison with FEM-simulations, representing an established simulation method, it can be shown that the self-developed model is able to accurately approximate the 3D electrostatic potential distribution of various contacted TEM-samples, whereby the computational complexity can be significantly reduced with respect to FEM-simulations (i.e.  $\sim 1000x$  faster with  $\sim 1/1000$ th of the memory usage at  $\sim 5000x$  more nodes). An excellent agreement can likewise be observed in comparison with electron holographic and tomographic investigations considering experimental restrictions, revealing the real potential distribution in propagation direction of the electron beam. By this, a significant reduction of the required computational power as well as a drastically simplified measurement process is achieved, paving the way towards quantitative electron holographic investigation of electrically biased semiconductor nanostructures. In particular, the latter can in turn also be used to understand the exact effects of the FIB-preparation (e.g. implantation concentration or implantation depth) on the sample, thus leading to improved preparation strategies.

**Graphic:**



**Keywords:**

Electron-Holography, Semiconductor-Nanostructures, 3D-Potential-Distribution, Surface-Effects, Computational-Optimization

**Reference:**

- [1] S. Yazdi et. al., Ultramicroscopy 152, 10 (2015).
- [2] D. Cooper et. al., Journal of Microscopy 233, 102 (2009).
- [3] A. C. Twitchett-Harrison et. al., Nano Lett. 7, 2020 (2007).