

Electron Holography of CMOS Devices with Epitaxial Layers

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Epitaxial SiGe and SiC(P) layers are used in the Source and Drain regions of the CMOS device to increase hole or electron mobility by imposing compressive (for p-FET device) or tensile (for n-FET device) stress in the channel region of the device [1,2]. Mapping of electrostatic potential in such devices with electron holography faces two new issues. First, the mean inner potential (MIP) of the epi layer $V_{\text{epi}}(\mathbf{r})$ should be known, because it needs to be subtracted from the total potential available from the reconstructed phase image $\varphi(\mathbf{r})$:

$$V_{\text{dopant}}(\mathbf{r}) = \varphi(\mathbf{r}) / (C_e t) - V_{\text{epi}}(\mathbf{r})$$

Here $\varphi(\mathbf{r})$ - phase image, C_e - interaction constant, t - sample thickness, $V_{\text{epi}}(\mathbf{r})$ - MIP of the epi layer, $V_{\text{dopant}}(\mathbf{r})$ - potential due to doping. Second, samples in holography analysis are tilted away from the zone axis by few degrees to minimize diffraction effects caused by Si or the epi layer. Therefore the epi layer overlaps with Si in the electron beam direction. Given that Si and the epi layer may have different MIP sample tilt makes it difficult to extract potential caused by doping from the phase image. After review of these problems the following results will be presented. All holography data was acquired on JEOL-2010F TEM. The holography reconstruction package developed by Prof. Molly R. McCartney was used for reconstruction [3].

Measurement of MIP in SiC and SiGe. MIP of SiC with the C= 4% total Carbon content and Cs= 1.4% Carbon substitutional fraction was measured from SiC/Si structures in x-section. Both SiC and Si were undoped. Difference between MIP of SiC and Si was found below 0.1V, i.e. the measurement error of the experiment. MIP of undoped $\text{Si}_{0.82}\text{Ge}_{0.18}$ was measured using p-FET devices with epi layers for two cases of a strain state of SiGe, i.e. when it was either almost relaxed or its lattice was under compressive strain. The latter was achieved through formation of misfit dislocations at Si/SiGe interface. Strain was measured from the same samples used for measurement of MIP. Strain was evaluated by Nano Beam Diffraction using F-strain algorithm [4]. Results indicate dependence of MIP of SiGe on the strain state (Table 1).

Analysis of Si:C films and Si:C based devices. Clusters formed by Si and interstitial Carbon have been observed in undoped $\text{Si}_{1-x}\text{C}_x$ films by conventional TEM. The cluster size increases with the total Carbon content, or concentration of the interstitial Carbon in the Si lattice. Electron holography has determined that clusters are negatively charged. Evidence of negative charging and an incomplete Phosphorus dopant activation was observed in n-FET devices, which were fabricated with the epitaxial $\text{Si}_{1-x}\text{C}_x$ (P) in the source and drain regions (Fig. 1)

Analysis of p-FET devices with epi-SiGe. Up to now sample tilt has restricted analysis of the dopant potential only to the regions close to the device channel, thus limiting its value. We suggest a method to correct for the sample tilt. It assumes that Si/SiGe interface is compositionally sharp and the MIP of SiGe is known in advance. The width of the Si/SiGe interface as viewed in the holography analysis and the position of the Si/SiGe interface as viewed along the zone axis are derived from the reconstructed

amplitude image. A parameterized erf-type function is fitted to the amplitude image to minimize effect of noise. These parameters are used then to correct potential image for tilt and the difference between MIP of Si and SiGe. As the result the dopant potential in the whole device can be evaluated (Fig. 2). Examples of analysis of dopant potential in p-FET devices and their correlation with electrical device data will be provided.

References:

- [1] B. Jin, J. Brask, S. Datta, G. Dewey et.al. in Electrochem.Soc. Proc (2004) vol. 2004-07, pp. 111-122
- [2] B.(Frank) Yang, R. Takalkar, Z. Ren et.al., IEDM Tech.Dig., 51 (2008)
- [3] M. R. McCartney, Software package for reconstruction in electron holography
- [4] F. H. Baumann, F-STRAIN: Software algorithm for extraction of strain from nanobeam diffraction data (to be published)
- [5] Authors acknowledge L. Kimball (IBM) for technical help.

SiGe strain state	MIP, V	$(d_{220}/d_{220}^{Si})-1, \%$	$(d_{400}/d_{400}^{Si})-1, \%$
Almost relaxed	12.85	0.6	0.7
Under compressive stress	13.03	-0.05	0.0

Table 1. Mean Inner Potential of Si_{0.82}Ge_{0.18}

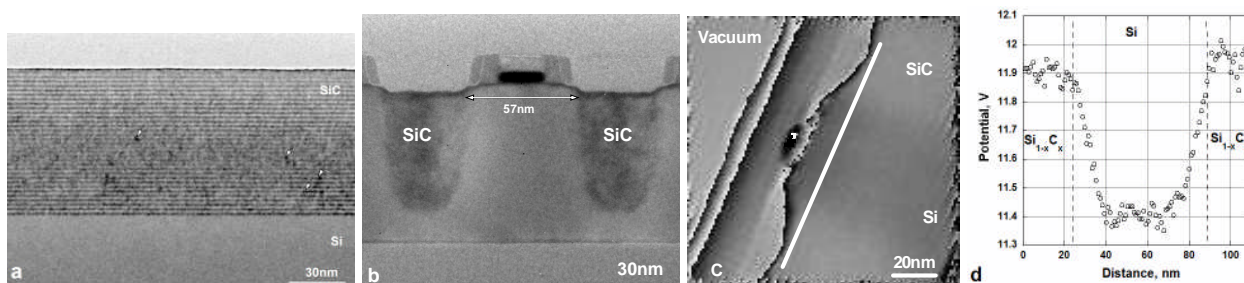


Fig. 1 (a): Conventional TEM image of Si/Si_{1-x}C_x with substitutional Carbon fraction Cs=1.4%. Clusters in Si_{1-x}C_x are arrowed; (b): n-FET device with similar Si:C film in Source-Drain regions; (c): Potential image of n-FET device; (d): Potential profile along the line shown in (c).

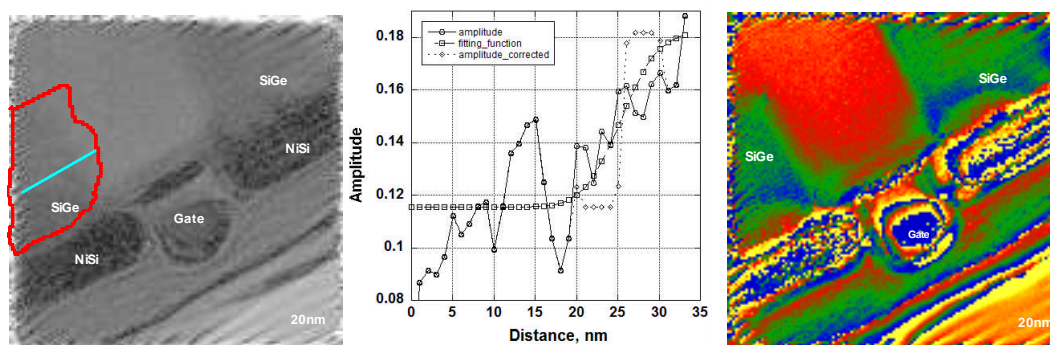


Fig.2. Left: amplitude map; Region for fitting is shown; Center: profile of amplitude, corrected amplitude and fitting function along the line shown in the amplitude image (left); Right: dopant potential after correction for sample tilt and difference of MIP between SiGe and Si.