Photon Energy Dependence of Contrast in Photoelectron Emission Microscopy of Si Devices

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Abstract

We investigate the variation in doping-induced contrast with photon energy in photoelectron emission microscopy (PEEM) images of Si pn devices using a free-electron laser (FEL) as a tunable monochromatic light source. Photoyield is observed from p-doped regions of the devices for photon energies as low as 4.5 eV. Band tailing is the dominant effect contributing to the low energy photoyield from the heavily doped p-regions. The low intensity tail from the n-regions, however, may be from surface states.

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We have previously reported that in near-threshold photoelectron emission microscopy (PEEM), image contrast can arise due to differences in semiconductor bulk doping concentrations[1,2]. The dependence of the photothreshold on the amount of doping can be attributed to surface state associated band bending[3]. In a p-type semiconductor with donor-type surface states, the resulting upward band bending generates a depth dependent photothreshold, which decreases from a maximum value at the surface to a minimum in the bulk. The depth at which the minimum is reached depends on both the bulk doping level and distribution of surface states. Using a fixed band gap, simple modeling of emission from the valence band would suggest that doping contrast in PEEM would increase by imaging closer to threshold. In this letter, we report on the use of a free-electron laser (FEL) as a high intensity, tunable monochromatic light source for PEEM imaging. We find a significantly higher photoyield from heavily doped p-type regions compared with lightly doped n-regions on Si(001) extends to photon energies at a least a few tenths of an eV below the conventional threshold, but contrast between different p-doping regions does not improve.

A commercial PEEM (Elmitec) is coupled to the Duke UV FEL. The sample is imaged in a chamber whose base pressure is $5x10^{-10}$ Torr. This system has been described fully elsewhere[4]. Briefly, the microscope includes a magnetic objective lens, a total magnification of 10,000x and a nominal resolution of approximately 10 nm. The FEL storage ring[5] produces coherent UV radiation in the range of 3.5 to 6.4 eV as well as spontaneous radiation from IR to soft X-rays. The results here were obtained using spontaneous radiation in the energy range of 4.5 to 5.2 eV with an average power of roughly 1mW focused to approximately 10 W/cm^2. The typical output spectrum of the FEL is nearly gaussian with a full-width at half maximum of approximately 0.13 eV.

The samples used for the study were fabricated using a combination of standard photolithography and focused-ion beam (FIB) writing techniques. A lateral array of pn junctions was formed by implanting boron ions (10^{18} cm^{-3}, 190 keV) through a mask into an n-type Si(001) substrate (P 10^{14} cm^{-3}). Additional lines were produced using FIB writing with 120 keV boron ions to allow a systematic variation of the doping levels. Lines were produced with nominal p-type bulk doping levels of 10^{18}, 10^{19}, 10^{20} cm^{-3} and nominal line widths of 200 nm. Subsequent to implantation the samples were annealed at 1050 °C for 20 minutes to activate the dopants. The average doping level in the sampling region is different than the bulk value. Using Suprem-IV[6], we estimate the near surface doping levels to be 10^{17}, 10^{18} and $3x10^{19}$ cm^{-3} for the corresponding bulk values mentioned above. No chemical etching was done prior to loading into the PEEM chamber, and a native oxide was present on the Si surfaces.

To analyze the PEEM intensity from the image data, line scans perpendicular to the implanted lines were measured for each set of doping levels. In a given image, 20 to 30 parallel scans were averaged to produce an intensity profile across the doped lines of interest.

A representative PEEM image showing doping contrast is illustrated in the inset of Fig. 1. The vertical lines are p-type ($3x10^{19}$ cm^{-3}), generated with FIB writing, and appear much brighter than the surrounding n-doped substrate. The horizontal lines (p-type 10^{18} cm^{-3}) of intermediate intensity were produced with standard broad-beam implantation through a photolithographically produced mask. Even higher intensity is observed for FIB lines with concentrations of 10^{20} cm^{-3} (not shown, see ref. 1). At this setting of the objective lens, the FIB lines are in sharp focus, but the photolithography lines are out of focus. To characterize the contrast seen in figure 1 quantitatively, we acquired images of the different lines with photon energy from 4.5 to 5.2 eV in steps of 0.1 eV. Figure 1 shows an example of our results, consisting of intensity scans across PEEM images of a pair of photolithography lines. The intensity increases monotonically as the photon energy increases. The contrast between p- and n- regions is observed for photon energies well below the nominal photothreshold of 5.1 eV, suggested by Allen and Gobeli for Si(111)[3]. Significant intensity from the n regions is visible for $h\nu$ greater than or equal to 4.8 eV.

The variation in image intensity peak height observed for each of the three different implantation concentrations is summarized in Fig. 2. The data were normalized to the calculated photoyield for a dopant concentration $N_a = 1\text{x}10^{17}$ cm^{-3} and a photon energy of 5.2 eV. Both the intensities and the contrast between the n and p regions drop with decreasing photon energy. The contrast between the p-stripes and the n-doped substrate remains observable down to 4.9 eV for the 10^{17} cm^{-3} stripe, 4.7 eV for the 10^{18} cm^{-3} stripe and 4.5 eV for the $3\text{x}10^{19}$ cm^{-3} stripe.

Allen and Gobeli showed that the photothreshold for a cleaved Si(111) surface decreases when the sample is heavily to degenerately doped[3], consistent with the monotonically increasing photoyield with dopant concentration we observe in Fig. 2. To make a quantitative comparison of the observed photon energy dependence of the photoyield with that expected for electron excitation from the valence band, we perform a standard model calculation. The photoyield Y from the valence band for an indirect optical transition near threshold can be expressed as

$$Y(h\nu) \propto \int (h\nu - E_T(x))^{5/2} e^{-x/l} dx$$

where $h\nu$ is the photon energy and $E_T(x)$ is the photothreshold as a function of bulk depth x[7]. The reduced escape depth l = 18 Å is given by $1/l = 1/l_\alpha + 1/l_e$ where l_α (approx. 60 Å) is the absorption length and l_e (25 Å) is the electron escape depth. The band bending profile, $E_T(x>0)$, is determined by solving Poisson's equation in the space charge region[8]. To determine the normalized surface potential v_s (defined as qV_s/kT), charge neutrality is invoked. By solving the neutrality condition as a function of v_s, the physically acceptable value of v_s can be determined[9]. The continuous distribution of surface states for a native oxide covered Si surface is parabolic[10] and centered at branch point energy $E_b - E_{vs}$ = 0.36 eV[11]. To calculate the photoyield from the p regions, we consider the effect of an areal surface state density $N_{sd} = 5\text{x}10^{13}$ cm^{-2}. In this case, the values of v_s range from 6.6 to 9.9 for doping levels 10^{17} to 10^{20} cm^{-3}. We calculate the p-stripe photoyield using these values of v_s.

For heavily doped silicon, impurity band tailing effects will reduce the band gap[12,13] which will also reduce the surface photothreshold, $E_T(x=0)$. Hence, we must treat $E_T(x=0)$ as a function of the bulk doping. For boron doping concentrations of 10^{18} cm^{-3} and higher, Wagner has shown that band gap reduction ranges from 50 to 200 meV [12].

The lines plotted with the data points in Fig. 2 show the results of calculations of the p-region photoyield, using the approach outlined by Kane for emission from the valence band[7]. The total calculated photoyield was obtained by integrating $Y(h\nu)$ over the distribution function of photon energies characterizing the FEL light source[4]. A gaussian distribution of photon energies centered about the desired photon energy with a full-width at half maximum of 0.13 eV was used as a weighting function in the integration. The best agreement of the calculated intensity variation with our data was obtained for surface photothreshold greater than predicted by Wagner. Using a nominal surface photothreshold of 4.9 eV, we find that band gap reductions of 25 meV ($E_T(x=0) = 4.88$ eV) and 40 meV ($E_T(x=0) = 4.86$ eV) produce good agreement with our 10^{18} and $3x10^{19}$ cm^{-3} data, respectively. We did not implement gap reduction for the 10^{17} cm^{-3} case since none is expected. We note that channel plate saturation may have reduced the measured intensities for 10^{18} and $3x10^{19}$ cm^{-3} at 5.2 eV.

For the lightly doped n-regions, the sub-threshold intensity is consistent with emission from occupied surface states. Low-level intensity would be expected down to approximately 0.4 eV lower than our best-fit surface photothreshold of 4.9 eV. In contrast, surface state emission from p-doped regions would only extend to approximately 0.2 eV below threshold.

Our previous study[1] using a Hg arc lamp ($h\nu \leq 5.1$ eV) produced results which could be explained reasonably well without considering the effect of impurity band tailing on the band gap. However, these results, in which we tune the photon energy, demonstrate that the effect of impurity band tails must be considered to correctly describe the photoyield data.

In summary, we have investigated the photon energy dependence of doping-induced contrast in PEEM. By using a tunable light source, we have, unexpectedly, been able to observe contrast between heavily p-doped regions and the lightly n-doped Si(100) substrate for photon energies as low as 4.5 eV. A simple model calculation of valence band emission from the p-regions, which includes the effects of impurity band tailing and surface state associated band bending, gives good agreement with our intensity data. We attribute the low-level intensity from the lightly n-doped substrate to surface state photoemission.

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References

[1] V. W. Ballarotto, K. Siegrist, R. J. Phaneuf, and E. D. Williams, Surf. Sci. Lett. **461**, L570 (2000).

[2] M. Giesen, R. J. Phaneuf, E. D. Williams, T. L. Einstein, and H. Ibach, Appl. Phys. A-Mater. **64**, 423 (1997).

[3] F. G. Allen and G. W. Gobeli, Phys. Rev. **127**, 150 (1962).

[4] H. Ade, W. Yang, S. L. English, J. Hartman, R. F. Davis, R. J. Nemanich, V. N. Litvinenko, I. V. Pinayev, Y. Wu, and J. M. Madey, Surf. Rev. Lett. **5**, 1257 (1998).

[5] V. N. Litvinenko, B. Burnham, J. M. J. Madey, S. H. Park, and Y. Wu, Nucl. Instrum. Methods Phys. Rev. **A375**, 46 (1996).

[6] Computer code Suprem-IV, Stanford University, Palo Alto, CA. Calculates 1- and 2-D implant profiles with pre- and post-annealing simulations.

[7] E. O. Kane, Phys. Rev. **127**, 131 (1962).

[8] H. Lüth, *Surfaces and Interfaces of Solid Materials*, **3**th edition (Springer, Berlin, 1995), Chap. 7

[9] W. Mönch, *Semiconducting Surfaces and Interfaces*, **2**nd edition (Springer, Berlin, 1995), Chap. 2

[10] H. Angermann, W. Henrion, M. Rebien, D. Fischer, J.-T. Zettler, and A. Roseler, Thin Solid Films **313-314**, 552 (1998).

[11] J. Tersoff, Phys. Rev. Lett **52**, 465 (1984).

[12] J. Wagner, Phys. Rev. B **29**, 2002 (1984).

[13] S. T. Pantelides, A. Selloni, and R. Car, Solid State Electronics **28**, 17 (1985).

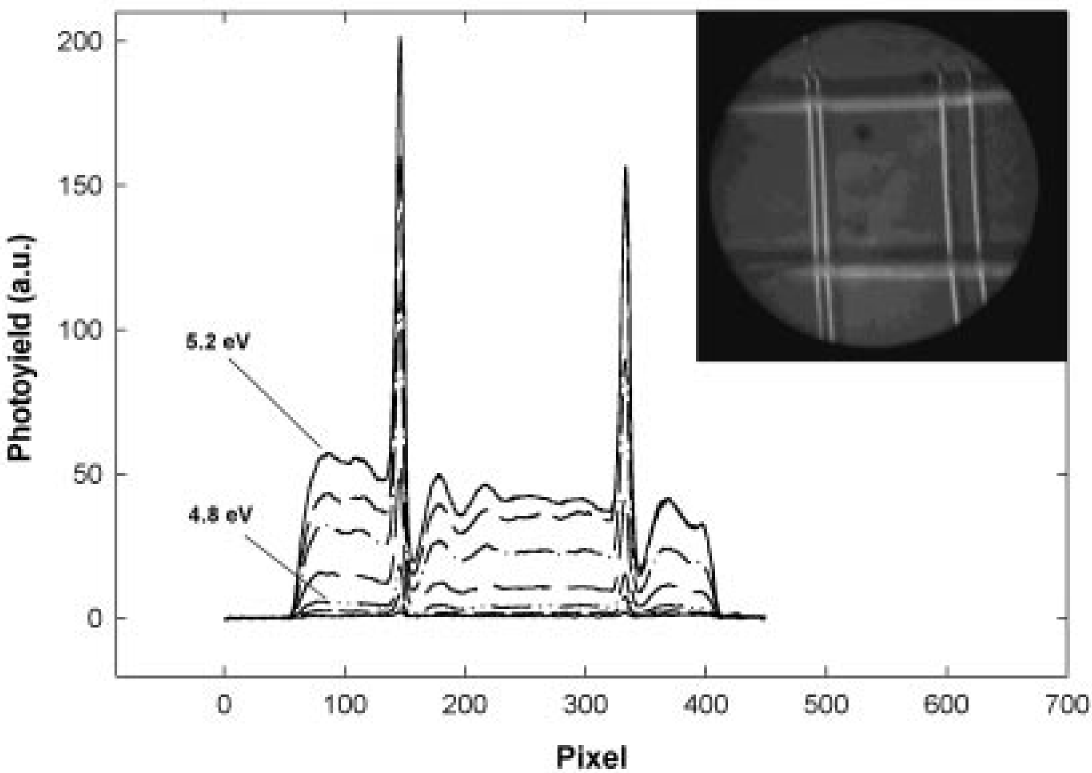

FIG. 1. PEEM intensity line scans of photolithography lines measured at different values of incident photon energy. Inset: PEEM image obtained with photon energy of 5.2 eV and displayed with a field of view of 50 um. The vertical lines are p-type ($3x10^{19}$ cm^{-3}) FIB lines. The horizontal lines are p-type (10^{18} cm^{-3}) photolithography lines.

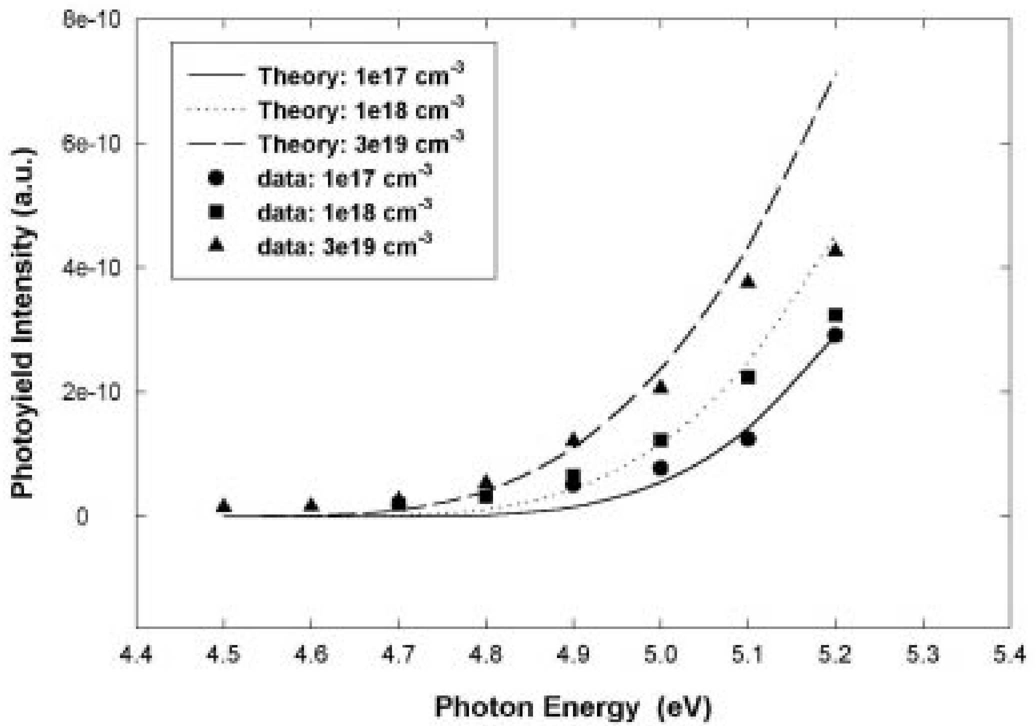

FIG. 2. Photoyield intensity as a function of photon energy. The symbols are measured values of PEEM intensity normalized to obtain agreement between measurement and calculation at 5.2 eV and $N_a = 10^{17}$ cm^{-3}. The curves show calculated intensity from the valence band.