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Contrast distortion induced by modulation voltage in scanning capacitance microscopy

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With a dark-mode scanning capacitance microscopy (SCM), we directly observed the influence of SCM modulation voltage (MV) on image contrasts. For electrical junctions, an extensive modulated area induced by MV may lead to noticeable changes in the SCM signal phase and intensity, resulting in a narrowed junction image and a broadened carrier concentration profile. This contrast distortion in SCM images may occur even if the peak-to-peak MV is down to 0.3 V. In addition, MV may shift the measured electrical junction depth. The balance of SCM signals components explain these MV-induced contrast distortions. © 2012 American Institute of Physics.

With a lock-in amplifier, scanning capacitance microscopy (SCM) sensitively detects differential capacitance (dC/dV) signals from material surfaces and map the dC/dV signal distribution (i.e., the SCM image), thereby qualitatively presenting material properties such as carrier type and concentration, defect distribution, ferroelectric domains, device structures, as well as dielectric quality. Among these applications, the ones essential for the function of SCM are imaging carrier types and concentration profiles. It is well known that the signal phase and intensity of SCM respond to carrier types and concentrations, respectively. Using SCM, one directly observes the electrical junction (EJ) profiles in electronic devices for investigating device processes (e.g., ion implantation and thermal annealing) and exhibiting device structures (e.g., source and drain regions). Due to the significance of signal phase and intensity, it is important to remove any artificial factors influencing the SCM measurements on EJ regions. For more than ten years, researchers have expended much effort to improving SCM and scanning capacitance spectroscopy (SCS): a technique for measuring local capacitance-voltage (C-V) characteristics. For example, Giannazzo et al. reported that the flat-band voltage shift induced by surface traps may lead to a hysteretic behavior of SCS, indicating the importance of specimen treatment. In 2003, Chang et al. revealed that the laser beam in an atomic force microscope (AFM) may induce a photovoltaic effect on the SCM images, highlighting the influence of the SCM setup on the observation of EJ regions. The SCS investigations by Buh et al. indicated that both the AFM laser beam and the modulation voltage (MV) may distort SCS profiles of a metal-oxide-semiconductor (MOS) capacitor. Moreover, the humidity-induced hysteretic behavior of SCS was studied, exploring the importance of environmental control for SCM measurements.

Since SCM is equipped with a lock-in amplifier to measure the dC/dV signals, it is necessary to apply a MV during SCM measurements. The applied MV induces a capacitance variation on the sample surface at a fixed dc bias for producing dC/dV signals. In general, one applies a higher MV to increase the dC/dV signal intensity, enhancing the phase contrast in SCM images. According to prior reports, the commonly used peak-to-peak MV may range from 0.3 V to 5 V for the acquisition of SCM images of EJ regions. However, a higher MV means that dC/dV signals are carried out from an extensively modulated area. This fact may perturb the SCM observation on EJ regions. In a typical SCM, it is difficult to completely remove photoperturbations, which may significantly distort the SCM images. There are many difficulties in identifying the MV influence on SCM images. For this reason, we employed dark-mode SCM to investigate the subtle influence of the applied MV on the SCM image contrast for the observation of EJ regions.

The samples used for this work were prepared on n-type (100) silicon wafers with a doping level of about $5 \times 10^{15}$ cm$^{-3}$. After growing a 250-nm-thick SiO$_2$ layer, a hard mask with a grating pattern (of which the window and spacing widths were designed to be 0.8 $\mu$m) was formed on the wafers via a deliberate photolithographic process, followed by reactive ion etching. After the hard mask formation, a BF$_2$ implantation at an ion-energy of 20 keV with an ion-dose of $5 \times 10^{14}$ cm$^{-2}$ was performed for all the samples. Subsequently, all the samples were treated by spike annealing (SA) followed by furnace annealing (FA) to form stable EJ regions. In each sample, more than 1500 identical junction sites were observed. The SA and FA treatments were performed at 1050 °C for 0.2 s and at 450 °C for 6 h in ambient N$_2$. After the FA, a tetraethylorthosilicate (TEOS) layer of 500 nm in thickness was grown on the patterned sample surfaces through plasma-enhanced chemical vapor deposition. Cross-sectional SCM specimens had been carefully prepared, in accordance with prior reports. According to the AFM, the root-mean-square roughness of the specimen surface is about 0.16 nm. A scanning probe microscope (Bruker D3100) equipped with an SCM module in National Nano Device Laboratories, Hsinchu, Taiwan, was used to obtain SCM images. The sensitivity of the capacitance sensor in the SCM system is as small as $10^{-22}$ F/(Hz)$^{1/2}$. The signal

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phases for p-type and n-type semiconductors are positive and negative, respectively. A shielding box, made in-house, was employed to control the environmental conditions, including temperature and humidity, for the SCM measurements. Commercially available solid-Pt probes (produced by Rocky Mountain Nanotechnology) with a tip height of about 100 μm were used to scan the sample surface. The force constant of the solid-Pt probes was 0.8 N/m. All the SCM images were obtained using the constant voltage mode (i.e., a fixed MV for each SCM image). The peak-to-peak MV ranged from 0.1 V to 2.1 V at 46 kHz and the dc sample bias for all SCM images was zero. In order to eliminate the influence of photoperturbations on SCM images, we used a two-pass technique, which is used in most commercial magnetic force microscopy (MFM) systems, to perform dark-mode SCM and to obtain EJ images. First, we acquired the AFM image and the corresponding SCM image from the sample surface using a typical SCM setup (the first pass in Fig. 1). This was done to examine the surface conditions, align SCM parameters, and obtain the surface morphology as a reference for subsequent dark-mode SCM measurements. The AFM laser was 670 nm in wavelength and 1 mW in output power. In the second pass, the SCM scanner followed the trace obtained in the first pass to obtain the corresponding SCM image with the AFM laser off. Of the two SCM images, the first SCM image is photoperturbed, while the second one is non-photoperturbed.

Figures 2(a)–2(e) show the dark-mode SCM images of the implanted region for various applied MVs. From Fig. 2, it is obvious that increasing the MV may shrink the green band, i.e., the observed depletion region. At the same time, the area with signals of positive phase broadened as the MV increased, implying that the observed p-type region also broadened with the MV. The above results are independent of the scanning order, in other words, from Fig. 2(a) to Fig. 2(e) or from Fig. 2(e) to Fig. 2(a). According to our previous study, photoperturbations may induce the same variations in the SCM images of EJ regions. However, photoperturbations did not occur within the results in Fig. 2 since the photoperturbation problem was removed by the dark-mode SCM setup. From the sectional analysis of the SCM images in Fig. 2, one observes that MV alters the \( dC/dV \) signal distribution of EJ regions. Figure 3(a) shows the depth profiles of the \( dC/dV \) signals for various MVs. According to the section analysis of Figure 2(a), labels I, II, III, and IV in Figure 3 denote the regions with their various phase and intensity responses. Region I exhibits zero signal because this area is a TEOS film. Regions II and IV exhibit a positive signal phase (p-type) and a negative signal phase (n-type), respectively. It is also clear that \( dC/dV \) signal intensity in regions II and IV increases with the MV since the MV enhances \( dC/dV \) signal intensity. In addition, the signals in region II exhibit non-monotonic behavior due to the wide range of carrier concentration in this region. Therefore, there is a higher carrier concentration region in which the signal intensity decreases with carrier concentration, while there is a lower carrier concentration region in which the
signal intensity increases with carrier concentration. The $dC/dV$ signal intensity in region IV does not exhibit the non-monotonic behavior seen in region II because of the silicon substrate with a low doping level. Region III indicates the area without signal response, i.e., a neutral area between $p$- and $n$-type regions in Fig. 2(a). This area is qualitatively defined as the depletion region. With the MV varying from 0.1 V to 0.9 V, the phase response of the $dC/dV$ signals in the $p$-type side of region III changes from neutral to positive. Meanwhile, the phase response of the $dC/dV$ signals in the $n$-type side of region III changes from neutral to negative. These signal variations lead to a narrowed depletion region or the narrowed green band. Figure 3(b) shows how the MV relates to the width of the observed depletion region. It is clear that the observed depletion region quickly shrinks as the MV increases. The width of the observed depletion region is down to zero when the MV is higher than 0.7 V. There exists a neutral point between positive- and negative-phase regions. For the MV ranging from 0.7 V to 0.9 V, the neutral point is fixed and referred to as the EJ position.23 Figure 3(b) indicates that the precise control of the MV in SCM is important even if only for the qualitative observations of a depletion region. Considering the general diameter range of a conductive tip, it is suggested that the peak-to-peak MV for reliable SCM measurements of EJ regions should be lower than 0.3 V.

When further discussing the MV-induced image contrast distortion, we first considered an EJ modulated by a low and a high MV. Figures 4(a) and 4(b) show a schematic EJ region modulated at a low MV and a high MV, respectively. In these figures, the tip positions L, C, and R schematically denote the depletion region boundary near the $p$-type region, the center of the depletion region, and the depletion region boundary near the $n$-type region, respectively. With a low MV, the $dC/dV$ signals at the L and R tip positions are close to the signal at the tip position C since all of the modulated areas are in the depletion region. As the MV increases, the modulated area is extended. A part of the $p$-type area may even be involved in the modulated area when the tip is located at the position L, as shown in Fig. 4(b). The same discussion is also applied to the tip position R. Taking a closer look at the $dC/dV$ signals of the tip positions L and R in Fig. 4(b), Fig. 4(c) shows a conductive tip working on a sample surface and that a modulated area is beneath this conductive tip. Since the total capacitance ($C_{\text{total}}$) is a superposition of the capacitance components in the modulated area, the total capacitance beneath the conductive tip is described as follows:

$$C_{\text{total}} = C_1 + C_2 + C_3,$$

where $C_1$, $C_2$, and $C_3$ are the effective capacitance of the modulated area close to the $p$-type side, the effective capacitance at the center of the modulated area, and the effective capacitance of the modulated area close to the $n$-type side.
respectively. From Eq. (1), the total $dC/dV$ signal is written as three signal components

$$\frac{dC_{\text{total}}}{dV} = \frac{dC_1}{dV} + \frac{dC_2}{dV} + \frac{dC_3}{dV}. \tag{2}$$

When the tip is at the position L in Fig. 4(b), $\frac{dC_1}{dV}$ has a positive phase response, and $\frac{dC_3}{dV}$ as well as $\frac{dC_2}{dV}$ are equal to zero. According to Eq. (2), the phase response of the total signal is positive. Similarly, the total signal phase is negative when the tip is at the position C in Fig. 4(b). For a high MV, the modulated area may be significantly extensive and contain the two boundaries of the depletion region even if the tip is near the position C. In this case, $\frac{dC_1}{dV}$ is still equal to zero, but $\frac{dC_2}{dV}$ and $\frac{dC_3}{dV}$ are in anti-phase of each other. With the tip moving from the position C to the position L, the positive signal phase is more and more dominant. On the other hand, the negative signal phase is dominant when the tip moves from the position L to the position R. The balance of $\frac{dC_2}{dV}$ and $\frac{dC_3}{dV}$ results in a neutral point or the observed EJ position. The above deduction is consistent with the prior report on delineating an EJ position by a symmetrical $C$–$V$ curve. \(^{23}\)

Due to photoperturbations, which induce junction narrowing, one easily observes the EJ position from the section analysis of SCM images of EJ regions at lower MVs. \(^{16,23,24}\) Since the observed EJ position is carried out from the balance of the signal components in a modulated area, the EJ depth is expected to depend on the MV. Figure 5 shows the measured EJ depth shifting toward the n-type region when the applied MV is higher than 1 V. With a fixed dc sample bias, a high MV may induce an asymmetrical $C$–$V$ curve, i.e., an imbalance of the signal components, because of the high carrier concentration gradient in the p-type region. The measured EJ position must move toward the n-type region to maintain a symmetrical $C$–$V$ curve. In other words, the observed EJ depth is deeper and deeper when the MV increases significantly. This implies that the MV may also disturb measurements on the EJ depth.

In summary, we have employed a dark-mode SCM to investigate the MV-induced image contrast distortion for the SCM observation on EJ regions. The extensive modulation induced by a high MV may lead to a false phase response, resulting in an obvious contrast distortion in the SCM images of EJ regions. This leads to the observed SCM images exhibiting junction narrowing as well as carrier distribution broadening. In addition, high-applied MVs may change the balance of the signal components in a modulated area, leading to a shift in the observed EJ position. Our experimental results have revealed that the $dC/dV$ signals of EJ regions are sensitive to the applied MV. For reliable SCM measurements on EJ regions, it is crucial to precisely control the MV.