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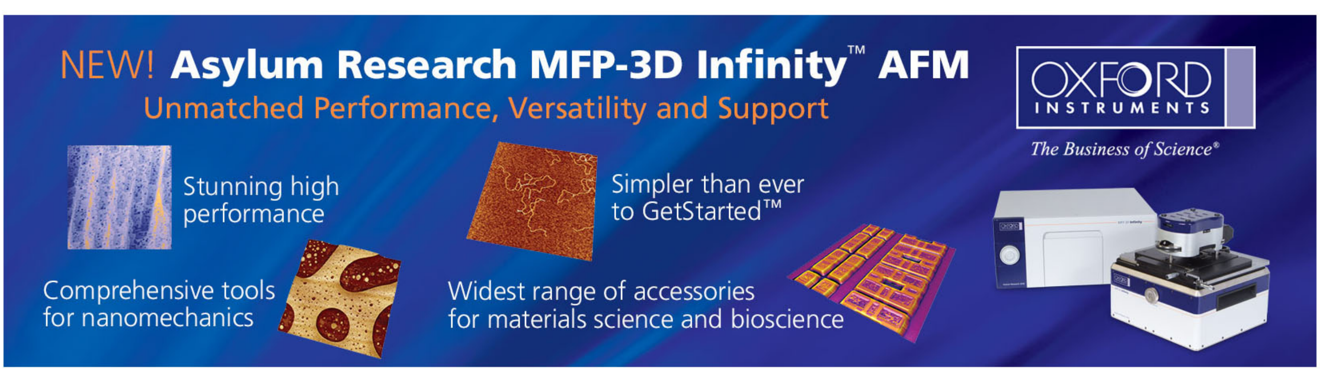

# Photovoltaic effect on the conductive atomic force microscopic characterization of thin dielectric films

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The authors have used front-wing conductive probes to investigate the photovoltaic effect on the conductive atomic force microscopic (C-AFM) characterization of thin dielectric films. The surface photovoltage induced by the laser beam of an atomic force microscope can enhance the electrical field across the studied dielectric film, decreasing the onset voltage of the leakage current, resulting in a modified C-AFM image with a larger current distribution. Moreover, the experimental results also revealed that the influence of the photovoltaic effect on C-AFM would be more significant for dielectric films that are grown on a substrate with a higher carrier concentration. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2357873]

Electrical scanning probe microscopy (E-SPM) is one promising method for studying the electrical properties of a nanometric area in electronic materials.[1–5] Among the E-SPM techniques, conductive atomic force microscopy (C-AFM) and scanning capacitance microscopy (SCM) are two well-known techniques for the characterization of thin dielectric films. In contrast to SCM, the C-AFM technique can also provide the local current distribution, and has been widely used to investigate the nanoscale current-voltage (*I*-*V*) characteristics as well as the breakdown mechanism of thin dielectric films.[6–8] Typically, an atomic force microscope (AFM) is equipped with a current sensor to synchronously provide current images to the corresponding topographic images. However, it has been revealed that an AFM laser beam can induce photoperturbation, which leads to difficulty in doing the SCM characterization of the carrier distribution and electrical junctions.[9] For instance, photoperturbation can lead to false SCM images and distorted differential capacitance versus bias curves.[10,11] Since C-AFM and SCM are based on the same AFM apparatus, it is thus natural to ask whether C-AFM also suffers from the same photoperturbation problem. Recently, Chang *et al.* found that a conductive probe with a front-wing (FW) cantilever, which provides an effective shadowed area that fully covers the scanned region, is a practical approach for nonphotoperturbed SCM characterizations.[12] In this present work, we have employed FW conductive probes to perform nonphotoperturbed C-AFM measurements and to qualitatively study the influence of the photovoltaic effect on the C-AFM characterization.

To investigate the influence of photoperturbation on C-AFM, various samples with an insulator-on-semiconductor structure were prepared. Samples 1 and 2 consisted of a lightly doped *p*-type ⟨100⟩ Si wafer covered with thermally grown $SiO_2$ thin films 2.5 and 5 nm in thickness, respectively. The carrier concentration of the lightly doped substrate was about $5\times10^{15}$ cm$^{-3}$. Sample 3 had the same *p*-type Si substrate, but with a 4-nm-thick $HfO_2$ film deposited on the substrate by atomic vapor deposition (AVD) using an AIXTRON Tricent system. After the AVD process, sample 3 was annealed at 900 °C in ambient $N_2$. Sample 4 consisted of a 2.5-nm-thick $SiO_2$ thin film that was thermally grown on a heavy-doped *p*-type Si wafer. The carrier concentration of the heavy-doped substrate was about $7\times10^{17}$ cm$^{-3}$. The thicknesses of the dielectric films were confirmed by a JEM 2010F high resolution transmission microscope operated at a 200 kV accelerating voltage.

All the AFM and C-AFM measurements were performed in an environment with well-controlled temperature and humidity, using an NT-MDT Solver P47 scanning probe microscope. The wavelength of the AFM laser ranged from 620 to 690 nm and the output power was 0.9 mW. To significantly reduce the current noise level of the C-AFM, we used a homemade shielding box for the scan unit. FW conductive probes with Cr–Co coated silicon tips (produced by MikroMasch) were used to scan the sample surface. These FW conductive probes allowed us to fine tune the photoperturbation level without problems in measuring topographic images.[12] The force constant of the cantilevers was less than 4 N/m. The back side of the cantilever was coated with an 80-nm-thick Cr–Co layer. To make the *I*-*V* measurements, negative biases were applied to the samples, since the *I*-*V* data would be unstable due to negative tip biases.[5] More than 50 surface sites on each C-AFM sample were measured under both photoperturbed and nonphotoperturbed conditions because repeated measurements at one point on the dielectric film could induce modified *I*-*V* curves.

Figure 1 shows four groups of the *I*-*V* curves obtained from samples 1 and 2. It is obvious that the photoperturbation has significantly reduced the onset voltage for both samples, implying that it is easier to detect leakage current from a sample surface with photoperturbations. In Fig. 1, we can also see that sample 1 had a higher onset voltage shift

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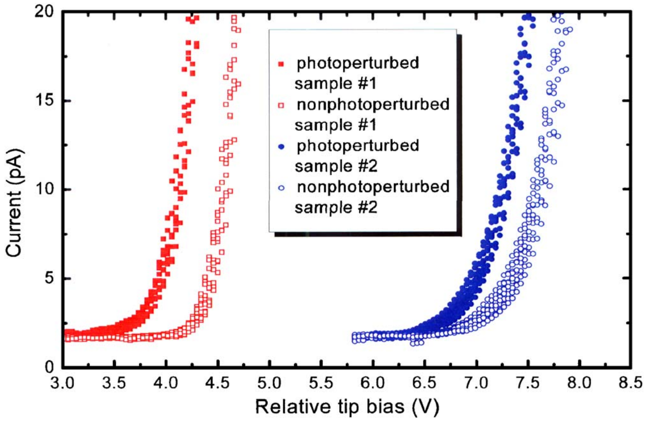


FIG. 1. (Color online) *I-V* curves obtained from samples 1 and 2, with and without photoperturbations. Although the illumination change is the same, sample 1 exhibits a higher onset voltage shift than sample 2 does.

than sample 2 for the same change in illumination. This result indicates that the influence of photoperturbation on C-AFM measurements depends on the thickness of the studied dielectric film. We attributed this result to the photovoltaic effect induced by the photoperturbations from the AFM laser beam. The total voltage drop $V_{total}$ during C-AFM measurement, for a sample without photoperturbations, can be generally described by

$$V_{total} = V_{ox} + V_d, \tag{1}$$

where $V_{ox}$ is the voltage drop of the dielectric film and $V_d$ is the voltage drop in the surface depletion region. At a constant negative sample bias $V_s$ with respect to the tip electrode, the electric field across the depletion region separates photogenerated electron-hole pairs and the minority carriers diffuse toward the illuminated surface, thus inducing the surface photovoltage that results in the potential change across the depletion region.[13] From the point of view of a circuit in equilibrium, the photovoltage will lead to the redistribution of voltage drops in the dielectric film and the depletion region, since the total bias remains constant. In other words, the photovoltaic effect can increase the voltage drop in the studied dielectric film and enhance the electrical field across the film. According to the above deduction, we can modify Eq. (1) for a photoperturbed C-AFM measurement as

$$V_s = V'_{ox} + V'_d = (V_{ox} + V_{pv}) + (V_d - V_{pv}), \tag{2}$$

where $V'_{ox}$ and $V'_d$ are the voltage drops in the dielectric film and the surface depletion region with photovoltaic effect, respectively, and $V_{pv}$ is the photovoltage induced by photoperturbation. From Eqs. (1) and (2), the photovoltage-induced change in the electrical field across the dielectric film can be described by

$$E_{en} - E_{ox} = \frac{V_{ox} + V_{pv}}{t_{ox}} - \frac{V_{ox}}{t_{ox}} = \frac{V_{pv}}{t_{ox}} = \Delta E, \tag{3}$$

where $E_{en}$ and $E_{ox}$ are the photoenhanced electrical field and the original electrical field of the dielectric film, respectively, $t_{ox}$ is the thickness of the dielectric film, and $\Delta E$ is the change in the electrical field induced by $V_{pv}$. Due to the existence of a positive $\Delta E$, the onset voltage could be reduced. Equation (3) also indicates that the photoperturbation-induced change in the onset voltage would be smaller for a

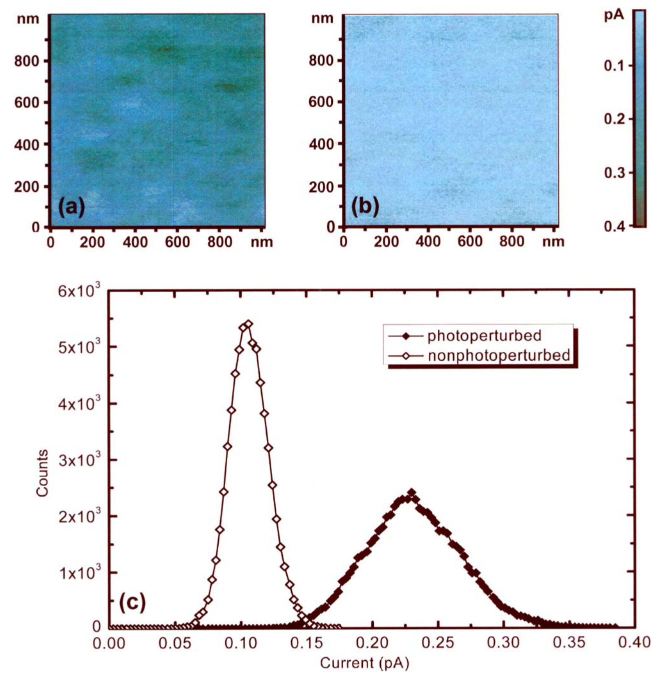


FIG. 2. (Color online) Current images ($1 \times 1$ $\mu m^2$) of sample 2 at a sample bias of −6.7 V (a) with and (b) without photoperturbation; (c) the statistical results of the current distributions corresponding to (a) and (b).

thicker dielectric layer, which is in agreement with the results shown in Fig. 1.

Figures 2(a) and 2(b) show current images of sample 2 at a sample bias of −6.7 V, with and without photoperturbation, respectively. It is apparent that, due to the enhancement of the electrical field across the $SiO_2$ film, the photovoltaic effect causes more significant current leakage on the sample surface. Figure 2(c) shows the statistical results for current distribution corresponding to Figs. 2(a) and 2(b). The full

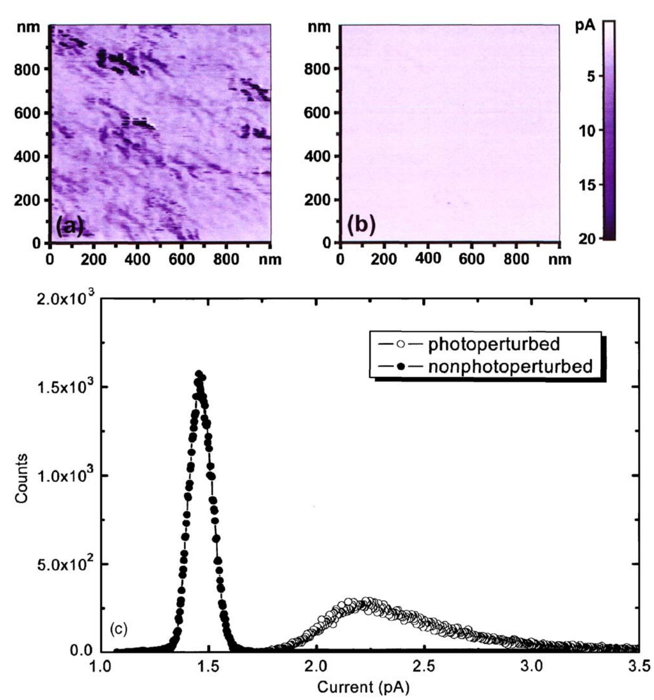


FIG. 3. (Color online) Current images ($1 \times 1$ $\mu m^2$) of sample 3 at a sample bias of −5 V (a) with and (b) without photoperturbation; (c) the statistical results of the current distributions corresponding to (a) and (b).

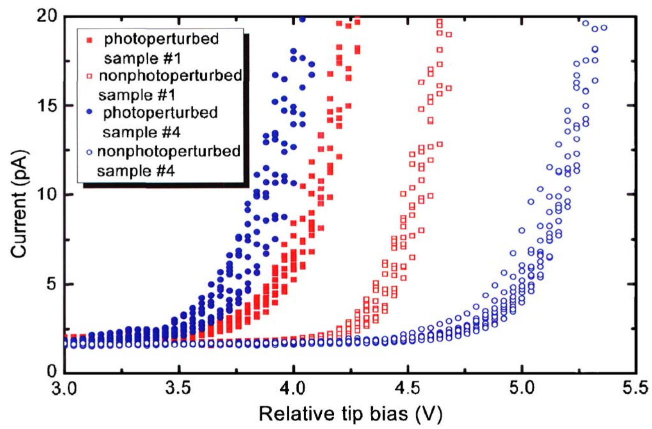


FIG. 4. (Color online) *I-V* curves for samples 1 and 4 with and without photoperturbations. Although the change in illumination is the same, sample 4 exhibits a bigger change in the onset voltage than sample 1 does.

widths at half maximum (FWHMs), with and without the photovoltaic effect, are 75 and 35 fA, respectively. The FWHM value can respond to the uniformity of current distribution on the sample surface. A more uniform current distribution will exhibit a smaller FWHM value. It is evident that the maximum distribution of the current signal increases with the photoperturbation level. The FWHM also shows the same trend. The statistical results in Fig. 2(c) reveal that the current distribution is able to sensitively respond to the illumination intensity, even if the current signals are very small. Figures 3(a) and 3(b) show the current images of sample 3 at a sample bias of −5 V, with and without photoperturbations. Since the photovoltaic effect can enhance an electrical field across a dielectric film, this photovoltaic effect may highlight the difference between areas in an $HfO_2$ film with different breakdown strengths. Figure 3(c) shows the statistical results for current distributions corresponding to Figs. 3(a) and 3(b). The FWHMs, with and without the photovoltaic effect, are 1.246 and 0.13 pA, respectively. This indicates that the photovoltaic effect may induce a significantly wider range of current distributions during C-AFM measurements when the dielectric film has the areas with weaker breakdown strength. From Figs. 2(c) and 3(c), one can expect that the FWHM value can also be a uniformity indicator of breakdown strength for thin dielectric films.

Figure 4 shows four groups for the *I-V* curves of samples 1 and 4. Since the photovoltaic effect may increase with substrate doping level,[14] the change in the electrical field across the studied dielectric films for dielectric films grown on a substrate with a higher carrier concentration will be more significant. As a result, with the same change in illumination there is a bigger change in the onset voltage exhibited by sample 4 than by sample 1, implying that sample 4 is more sensitive to photoperturbations during C-AFM measurement. Indeed, obvious current fluctuations frequently occurred during the C-AFM measurement of samples such as sample 4.

To summarize, we employed FW conductive probes to investigate the photovoltaic effect during the conductive atomic force microscopic characterization of thin $SiO_2$ and $HfO_2$ films. The photovoltaic effect induced by an AFM laser beam can lead to an enhanced electrical field across the dielectric film and hence result in false C-AFM images as well as modified *I-V* characteristics. Provided the illumination conditions are the same, the influence of the photovoltaic effect on the C-AFM measurements of an insulator-on-semiconductor structure is significantly dependent on the properties of the dielectric film and the carrier concentration in the semiconductor region. Thus, C-AFM measurements would be more stable and accurate without the photovoltaic effect. On the other hand, the photovoltaic effect can be employed to study dielectric breakdown in nanometric areas provided that the photoperturbation level in the C-AFM can be quantitatively controlled.


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