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Variations of differential capacitance in $SrBi_2Ta_2O_9$ ferroelectric films induced by photoperturbation

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In this letter, we demonstrated the impact of illumination on the differential capacitance variation of a strontium bismuth tantalite (SBT) capacitor during scanning capacitance microscopy measurements. It was found that illumination with a stray light of laser in an atomic force microscope could perturb the dC/dV signals of the samples. We attribute this phenomenon to the generation of free carriers by the photon absorptions via defect traps in the SBT thin film. Therefore, this present work suggests that the effect of laser illumination must be carefully taken into consideration whenever a field-sensitive technique is employed to analyze the properties of a ferroelectric material. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1879089]

Scanning capacitance microscopy (SCM) has attracted much interest for profiling the two-dimensional carrier distribution of both devices and memories, by determining the interface defect distribution at the SiO_2/Si interface, and by monitoring the local trapping in SiO_2/Si and III-V nitride systems through its high sensitivity and high spatial resolution.[1–5] In spite of all its advantages, it was recently discovered that SCM suffers severely from the illumination issue, i.e., photovoltaic effect, which has been demonstrated seriously impact upon the SCM signal output.[6,7]

In our previous work, SCM was introduced for visualizing the domain patterns in $SrBi_2Ta_2O_9$ (SBT) thin films, with the advantage of a nanoscale resolution.[8,9] Many photoelectronic effects, such as photoconduction, photoassisted domain switching, photoexcited space charge, and photovoltaic phenomena, have frequently been reported in ferroelectric materials.[10–15] Our concern is, to what extent can laser illumination influence the accuracy of an extracted SCM signal? In this study, we have demonstrated that a laser illumination incident across the cantilever onto the SBT thin film does affect the outcome of the SCM signals. By changing the incident position along the cantilever arm, it was found that the image contrast improved when the focus of the laser spot was moved away from the tip site.

An SBT ferroelectric thin film, with a thickness of about 210 nm on top of a Pt/TiO_2/SiO_2/Si substrate was studied in the present work. The sample preparation process has been reported previously.[16] The details of the SPM (Digital Instruments D5000) system used for dC/dV signal extraction are described in Ref. 8. The wavelength of the atomic force microscope (AFM) laser is 670 nm ($\sim$1.85 eV), and the output power is 1 mW (intensity $\sim$50 W/cm^2). Several of the mechanical settings for this examination are shown in Fig. 1. Figure 1(a) shows the standard setup for the AFM laser beam alignment on the cantilever tip site (Setup 1). Next, two different effective light intensities were created on the scanned region from Setup 1 by deliberately aligning the laser beam on either the middle [Fig. 1(b), Setup 2] or the bottom [Fig. 1(b), Setup 3] of the cantilever arm. Figure 1(c) shows a schematic of the setup and dimension of the cantilever and holder. Figure 1(d) displays the micrograph of the case illuminated with an externally guided green laser, superimposed on Setup 1.

The AFM and the corresponding SCM images of the SBT films acquired under the condition of Setup 1 are shown in Figs. 2(a) and 2(b), respectively, while Figs. 2(c) and 2(d) show the results of the analysis for Setup 2. For the sake of convenience, the markers, "+", were added to indicate the same sample position in both AFM and SCM images. When comparing the SCM images between Setups 1 and 2, it is

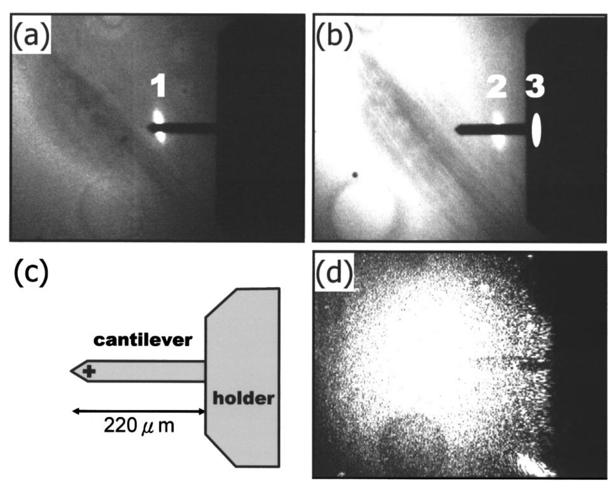

FIG. 1. (a) and (b) The three setups for the AFM laser beam illumination. Sites 1, 2, and 3 are located at the tip, the middle, and the holder of the cantilever, respectively. (c) Schematic diagram displaying the setups and the dimensions of the cantilever. The tip position is indicated by the marker, "+". (d) A green laser light spot aligned and superimposed externally on the tip of the cantilever.

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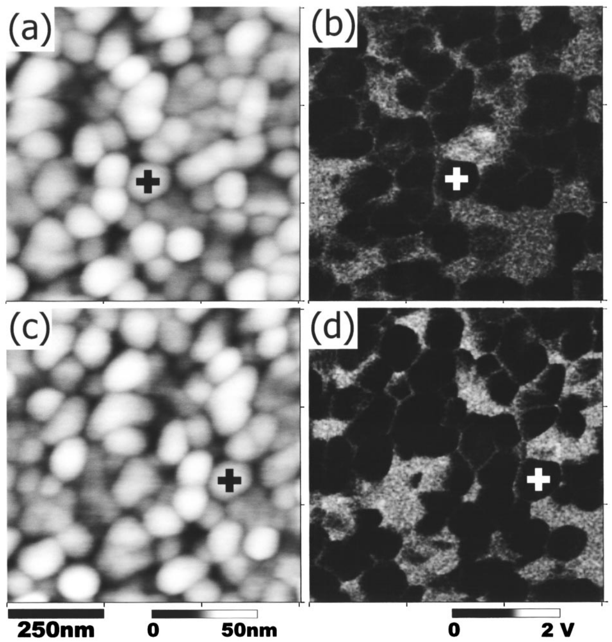

FIG. 2. Simultaneously obtained AFM and SCM images of a fresh SBT thin film for Setup 1 [(a) and (b)] and Setup 2 [(c) and (d)] under a voltage of 0 V.

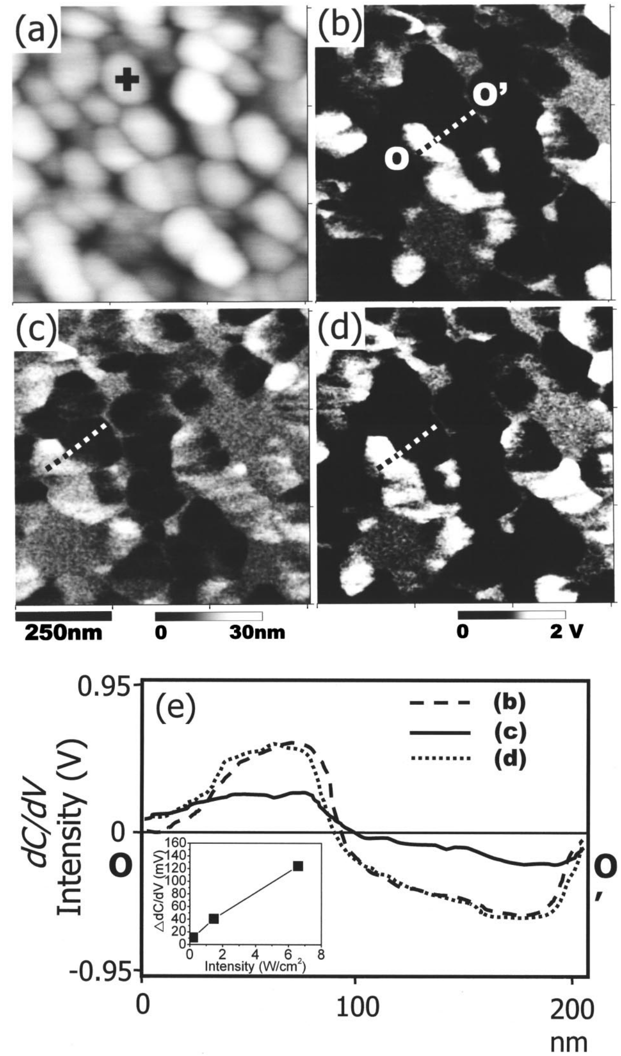

FIG. 3. (a) and (b) The AFM and SCM images of SBT thin film for the AFM typical setup (Setup 1), respectively. (c) The SCM image obtained in the same region with a green laser illumination. After turning off the green laser, the SCM image is acquired again and is shown in (d). All of the images are obtained with bias at 0 V. (e) Cross-sectional signal spectra along the OO' line marked on SCM images [(b), (c), and (d)]. Variations of the differential capacitance vs the green laser intensity inside one negative domain are shown in the inset.

evident that the contrast in Fig. 2(d) is sharper than that in Fig. 2(b). This suggests that the effective light intensity on the scanned region does have an influence on the dC/dV values. An even more significant improvement in the clarity of SCM image can be acquired by moving the laser beam further onto Site 3 (not shown here), but in that case, the corresponding AFM morphology image became greatly deteriorated. As a result, it was concluded that the red laser illumination does have a considerable influence on the extraction of the SCM image, and that the image quality degrades with the increase in incident light intensity, even though the photon energy is much less than the energy gap of SBT ($E_g \sim 4.2$ eV).[17,18] A plausible explanation is the generation of excited free carriers by photon absorption via the traps located inside the band gap of SBT.

To verify the point, an externally guided green laser with a photon energy of 2.34 eV (wavelength is 532 nm) and output power of 13.6 mW (intensity ~ 4.8 W/cm^2) was used for further study. The results, with and without green laser illumination, are shown in Fig. 3. Figures 3(a) and 3(b) display the AFM and the corresponding SCM images without the green laser illumination, respectively. A domain pattern with a sharp contrast was apparent. However, the contrast of the SCM image degraded significantly once the green laser was introduced, as is demonstrated in Fig. 3(c), and the extent of the change was much greater than in Fig. 2(d). It is worth noting that the contrast of the image was almost fully recovered once the green laser had been turned off, as shown in Fig. 3(d). In order to examine the dC/dV signal variation in detail, the cross-sectional signal spectra along the line marked as OO' on the SCM images of Figs. 3(b)–3(d) are shown in Fig. 3(e). It is apparent that the green laser illumination induced the decrease of the dC/dV value by more than 50% in both the positive and negative polarities. After turning off the laser, the dC/dV value recovered to almost the original level, except for a tiny shift. This indicates that this photoeffect is not permanent. Surface photovoltaic measurements on SBT films have been published previously and have shown a close relationship between the photovoltic response and the photoenergies of illumination.[18] Since, the photovoltaic effect is due to photoexcitation charges, the photovoltaic response implies the possibility to excite the free charges from material by illumination.[11,15] The resulting curve showed a threshold energy of about 1.8 eV and a significant increase in photovoltaic response (~ 40 mV) near 2.2 eV.[18] This suggests that there are plenty of excess Bi traps located near the level of 2.2 eV above the valence band. Consequently, in this study, the abundance of free charges could be generated through the green laser (2.34 eV) excitation of Bi traps. Therefore, the free charges generated by illumination can compensate for the depolarization field of SBT and lead to a deterioration of the image contrast.[19] The change of differential capacitance as a function of the green laser intensity was also investigated inside one negative domain, as shown in the inset of Fig. 3(e). The linear relationship between differential capacitance and illumination intensity is similar to the photovoltaic behavior in

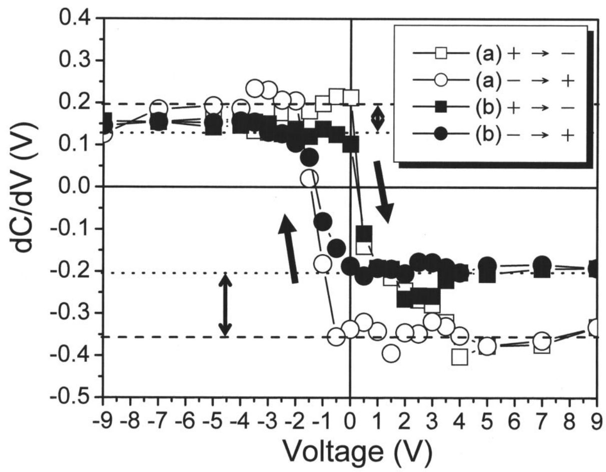

FIG. 4. The variations of dC/dV vs V without and with the green laser illumination are indicated as (a) and (b) hysteresis loops, respectively. dc bias (bottom electrode) is applied in the steps from 9 V to −9 V, and then increased again up to 9 V.

ferroelectrics.[15,20] In addition, the change in the dC/dV signal value reached 125 mV at a light intensity of 6.6 W/cm^2, which is much greater than that of red laser illumination (~30 mV), albeit the intensity of red light is seven times higher (50 W/cm^2). This indicates that the SCM variation, as well as the photovoltaic effect, is more sensitive to photoenergy than to light intensity.

For the purpose of examining the photoeffect on the switching properties in ferroelectrics, a local measurement was conducted at a large grain region marked with a "+", see Fig. 3(a). The hysteresis loops shown in Figs. 4(a) and 4(b) represent the cases without and with the green laser illumination, respectively. They are somewhat different from the results in the macroscopic measurement.[8,9] This difference can be attributed to the large lock-in ac modulation voltage (V_{ac}, 2 V) used in this study. By turning on the green laser, the absolute dC/dV values unequivocally decreased along the vertical axis accompanied by a slight decrease in the coercive field. In addition, the decrease in the negative dC/dV value is larger than in the positive one. Even though the cause of this effect remains unclear, a possible mechanism for this polarity dependent behavior may be the photocurrent, which is usually induced by the long-range migration of carriers. As is known, the SCM signals were extracted from the tip of the cantilever arm so that only the charges flowing through the tip could affect the dC/dV values. With the nonequivalent exciting efficiencies and drift velocities for an electron and hole, the magnitudes of the sensed photocurrent would be quite different for the two polarities. As a result, a relatively greater decrease of the dC/dV value was observed in the negative region compared to the positive region. With regard to the reduction of the coercive field, a similar trend has also been observed in previous reports.[12,21]

In conclusion, the differential capacitance variation induced by laser illumination was investigated. It was observed that the red laser does affect the dC/dV signal output, even though the photon energy of the laser light is less than the band gap of SBT. This phenomenon is believed to be closely related to the photogenerated free charges with the absorption of a stray laser light across the cantilever via the traps in the SBT. This result implies that the photoelectric effect may possibly appear in the SPM measurements and cause a significant impact on those field-sensitive detection methods.

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