200 femtometer sensitivity for near-field analysis of surface acoustic waves in a scanning electron / scanning probe microscope hybrid system

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(Received 12 February 2007; accepted 6 March 2007; published online 6 April 2007)

In the microscopic hybrid system, a combination of a scanning electron microscope with a scanning probe microscope, both microprobes are used for local generation and detection of acoustic waves in the near field. At the example of ferroelectric domain imaging, a sensitivity of 200 fm in the local detection of vertical surface oscillation is demonstrated whereas the spatial resolution is within several nanometers. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2721123]

Near-field detection is essential for modern microscopy techniques in failure analysis and reliability for materials and devices, since the achievable resolution in far field is limited by Abbé criterion to approximately half of the wavelength used for investigation.[1] Therefore, near-field conditions must be introduced, either for generation or for detection, to obtain better spatial resolutions. This can be performed by introducing apertures or modifying the source or detector characteristics such that they are different from point characteristics.[2] Due to the comparably large wavelength, nanoscopic investigations by means of acoustic waves imply near-field conditions.

In scanning probe acoustic microscopy techniques, a microprobe is introduced which is placed in the near field of a piezoelectric transducer. The microprobe, e.g., a scanning probe microscope (SPM) tip, optical or electron beam, can act either as a detector[3,4] or source[5,6] for acoustic waves and the transducer is taken for the other function, respectively. The scanning electron microscope (SEM)/SPM hybrid system implies two microscopes since a SPM is built inside the chamber of a SEM.[7] It has various applications for different modes of analysis.[8,9] In acoustic mode two microprobes can be used simultaneously for local generation and detection of acoustic waves. In this manner the electron beam acts as an acoustic source, and the resulting acoustic waves on the sample surface are detected with a SPM tip in contact. The experimental setup is shown in Fig. 1.

The electron beam is modulated locally by a saw function at the scan coils to generate a near-field source. This modulation results in the behavior of an acoustic line source of finite length with directed emission vertically to modulation direction.[10] A linear source has good near-field properties and is also often used in thermal microscopy techniques.[11] The acoustic waves propagate in the sample causing surface acoustic waves (SAWs) on the sample surface. Resulting surface oscillations are measured by a SPM tip in contact with laser deflection method and lock-in technique. The four-quadrant photodiode allows detection of vertical as well as lateral oscillation modes. The cantilever is placed in parallel to the source leading to direct correlations of the lateral cantilever oscillation to the in-plane component of the SAW and of the vertical oscillation to the out-of-plane component. In this alignment, due to linear emission, there is no in-plane component of SAW in the near field which would lead to cantilever buckling and an additional vertical signal. Source and detector are fixed with respect to each other in this setup, and the sample is scanned with piezotranslators. Amplitude and phase signals of vertical as well as lateral oscillations are recorded together with the topography during scan.

A barium titanate ($BaTiO_3$) ceramic is used as sample, which is ferroelectric at room temperature due to its perovskite-type crystal structure. It is often used for acoustic microscopy techniques[3,6] since it is a well-known material which shows a good acoustic contrast due to its mechanical inhomogeneities arising from the ferroelectric domains. The SAW distribution and thus the local oscillations depend on the domain orientation since the elastic and piezoelectric constants in the material vary with polarization angle.[12] Hence, the ferroelectric domain structure can be imaged by the measurement technique described above. Also domain orientation can be determined qualitatively, since vertical as well as lateral signals are detected.

In Fig. 2 the measurement results are shown obtained by a 15 keV electron beam modulated on a line of 43 μm length. Since the linewidth is about 2 μm (simulated by Monte Carlo method), the length is chosen much larger to achieve the linear characteristic. The modulation frequency is 76.8 kHz corresponding to an acoustic wavelength of about 4.4 cm. The cantilever oscillation is measured with lock-in amplifiers at a time constant of 40 ms. Vertical oscil-

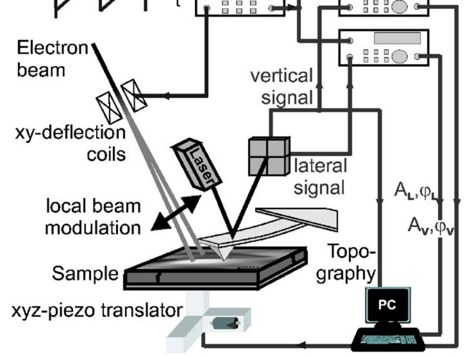

FIG. 1. Measurement setup of SAW near-field detection in the SEM/SPM hybrid system.

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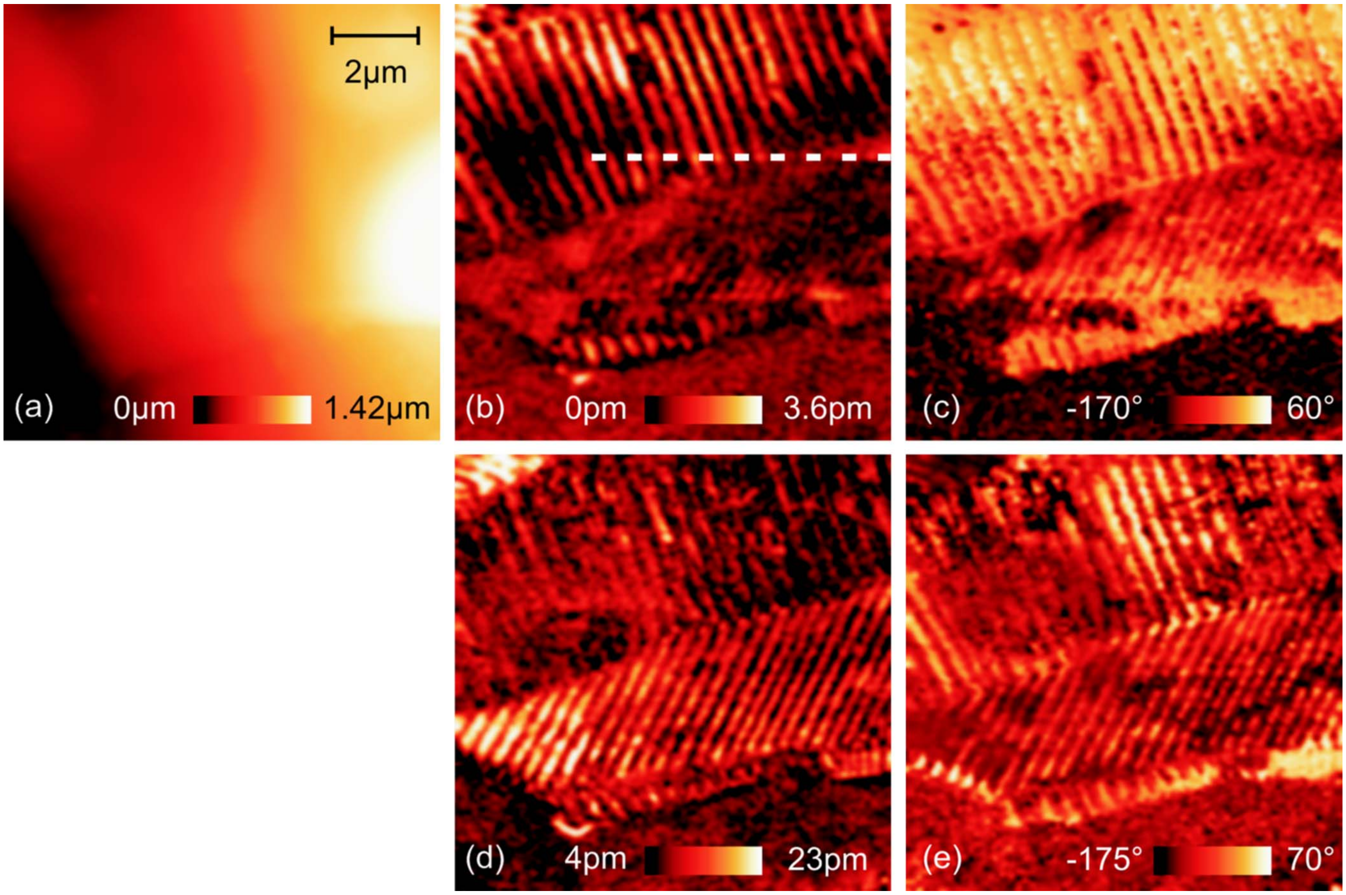

FIG. 2. (Color online) Acoustic imaging of ferroelectric domain structures in $BaTiO_3$: topography (a), vertical oscillation amplitude (b) and phase (c), and lateral oscillation amplitude (d) and phase (e).

lation amplitudes are calibrated by the SPM calibration curve providing the relation between cantilever deflection and measured photodiode signal (36.68 mV/nm). Quantitative lateral oscillation amplitudes depend on the cantilever geometry and are calculated according to Ref. 13.

The results show a good domain contrast in the acoustic images. Although the sample is not flat, topography has almost no influence on the acoustic contrast. Due to the directive emission of the source, the lateral oscillation amplitudes are higher than the vertical. The direction of polarization can be observed by comparing vertical and lateral oscillation images qualitatively. The investigated grain is divided into two parts, an upper part and a lower one. In the upper part domains are more vertically orientated, since the domain contrast is affected by the vertical oscillation and such contrast is better in the vertical than in the oscillation image. For the lower part the behavior is opposite revealing to more laterally polarized domains. From this it can be also demonstrated that the cross talk between vertical and lateral signals[14] can be neglected and hence both signals are quite independent of each other. Spatial resolution in the acoustic image achieved with this measurement technique is in the order of several nanometers and more than six orders of magnitude smaller than the acoustic wavelength.[15]

A sensitivity analysis of this technique is performed in an additional measurement on the same structure as above. This analysis is depicted in Fig. 3 and shows a slow line scan of the vertical oscillation amplitude on the line indicated in Fig. 2(b). It is performed with a lower electron beam current and a longer time constant (400 ms) reducing the noise. The domain structures in the upper part ($x<4$ μm in Fig. 3) are discontinuous due to a local disturbance of measurement. The noise reduction also enables domain detection in the lower part ($x>4$ μm in Fig. 3) for vertical oscillation. The sensitivity of vertical oscillation amplitude is evaluated from the graph to 200 fm (rms). It is limited by the noise of the hybrid system[7] which is reported to 310 fm/$Hz^{0.5}$ for frequencies higher than 50 kHz. The main noise sources in this setup are piezonoise, photodiode shot noise, and thermal noise of the cantilever. Of course the sensitivity could be further increased by a longer time constant of the lock-in amplifier and hence a further noise reduction. However, this

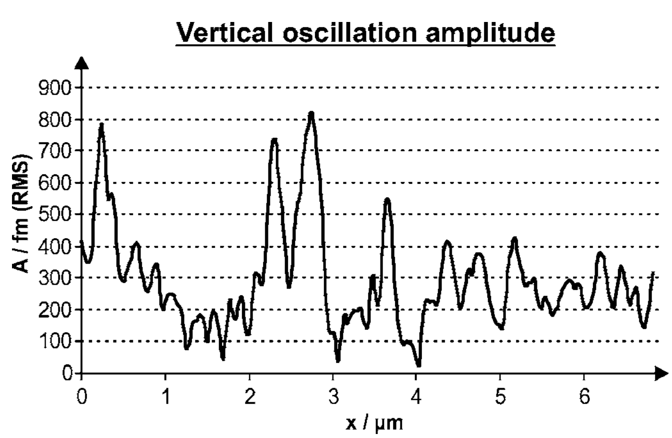

FIG. 3. Slow line scan of vertical oscillation amplitude [dashed line in Fig. 2(b)].

would cause problems with respect to the long time stability of the system, especially regarding piezotranslators and electron beam.

The sensitivity of 2×10^{-13} m (rms) is equal to a 570 fm vertical swing of the sample surface which still can be detected. To classify the dimension of the sensitivity, it can be compared to the lattice constant of $BaTiO_3$ ($\sim$400 pm at room temperature), which is more than three orders of magnitude larger than the achieved value. Only slightly more than a factor of 10 is between the sensitivity and the diameter of barium atomic nucleus ($\sim$12 fm).

Concluding, it can be stated that this acoustic microscopy technique basing on a near-field approach and combining two microprobes into one system has many advantages and can be applied to various acoustic investigations, not only for domain investigations. It has the convenience being independent of sample geometries since the near-field condition can be adapted. Further, no problems of acoustic matching occur as the acoustic source is directly implemented into the sample. At the same time, it still has a high performance as demonstrated with subpicometer sensitivity and nanometer spatial resolution.

[1] E. Abbé, Archiv f. Mikroskp. Anat. **9**, 413 (1873).
[2] L. J. Balk, R. Heiderhoff, J. C. H. Phang, and Ch. Thomas, Appl. Phys. A: Mater. Sci. Process. **87**, 443 (2007).
[3] U. Rabe, M. Kopycinska, S. Hirsekorn, J. Muñoz Saldaña, G. A. Schneider, and W. Arnold, J. Phys. D **35**, 2621 (2002).
[4] Q. R. Yin, G. R. Li, H. R. Zeng, X. X. Liu, R. Heiderhoff, and L. J. Balk, Appl. Phys. A: Mater. Sci. Process. **78**, 699 (2004).
[5] L. J. Balk, Adv. Electron. Electron Phys. **71**, 1 (1988).
[6] X. X. Liu, R. Heiderhoff, H. P. Abicht, and L. J. Balk, J. Phys. D **35**, 74 (2002).
[7] I. Joachimsthaler, R. Heiderhoff, and L. J. Balk, Meas. Sci. Technol. **14**, 87 (2003).
[8] A. Altes, I. Joachimsthaler, G. Zimmermann, R. Heiderhoff, and L. J. Balk, *Proceedings of 9th IPFA* (IEEE, New York, 2002), 196.
[9] Ch. Thomas, I. Joachimsthaler, R. Heiderhoff, and L. J. Balk, J. Phys. D **37**, 2785 (2004).
[10] Ch. Thomas, R. Heiderhoff, and L. J. Balk, J. Phys.: Conf. Ser. (to be published).
[11] A. Altes, R. Heiderhoff, and L. J. Balk, J. Phys. D **37**, 952 (2004).
[12] C. Harnagea, A. Pignolet, M. Alexe, and D. Hesse, Integr. Ferroelectr. **44**, 113 (2002).
[13] F. Peter, A. Rüdiger, R. Waser, K. Szot, and B. Reichenberg, Rev. Sci. Instrum. **76**, 046101 (2005).
[14] A. Hoffmann, T. Jungk, and E. Soergel, e-print cond-mat/0610167.
[15] Ch. Thomas, R. Heiderhoff, and L. J. Balk (to be published).