Acoustic near-field conditions in an ESEM/AFM hybrid system

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Abstract. The local distribution of acoustic waves generated by a locally modulated electron beam is investigated in a hybrid system consisting of an Environmental Scanning Electron Microscope (ESEM) and an Atomic Force Microscope (AFM). Depending on the modulation, different acoustic source characteristics with different near-field conditions are generated which can be used in acoustic near-field techniques, for example to detect ferroelectric domain structures.

1. Introduction

Scanning Acoustic Microscopy [1] is a widely used technique for failure analysis and reliability investigations of modern devices. Micro probes have been introduced to achieve resolutions below the wavelength. They can be used either as detector [2,3] or as source [4,5] of acoustic waves in combination with a large-area transducer. By combination of two micro probes, generation as well as detection of acoustic waves can be performed locally.

In this paper an electron beam is used for generation of acoustic waves which are detected by an AFM tip. By certain beam modulations the source can be varied to get different near-field properties. The source characteristics can also be simulated. As an application, ferroelectric domain structures can be investigated.

2. Acoustic sources generated by local electron beam modulation

Electron beams can be used as acoustic sources not only if they are chopped, but also if they are modulated locally. In this case a static source is moved periodically such that a wave is emitted. Due to different interaction mechanisms, the sample material is excited acoustically at the place where the electron beam interacts [4]. A locally modulated beam has the advantage that no beam blanker is required and the technique can be performed in every SEM.

To simulate the characteristic of such kind of acoustic source, the interaction of the beam is considered as a spherical structure with the diameter of the acoustic interaction volume and with a temporally as well as locally constant excitation. This sphere is shifted locally and periodically on the sample and a periodical excitation is obtained. That yields in an acoustic oscillation of the sample,
since the modulated path of the electron beam can be considered as a formation of many sources stringed together which are switched on and off.

The static excitation amplitude of the sphere is for isotropic materials [6]

\[
V(x, y, t) = \frac{A}{\sqrt{(x-x_0)^2 + (y-y_0)^2}} \quad \text{for} \quad \sqrt{(x-x_0)^2 + (y-y_0)^2} > R
\]

outside the sphere and

\[
V(x, y, t) = \frac{A}{2R} \frac{(x-x_0)^2 + (y-y_0)^2}{2R^3} \quad \text{for} \quad \sqrt{(x-x_0)^2 + (y-y_0)^2} \leq R
\]

inside the sphere, whereas \( A \) is the density of excitation, \( R \) is the sphere radius and \( x_0, y_0 \) are the coordinates of the sphere center. If this sphere is modulated locally with a periodic function at an excitation frequency \( \omega_0 \), the coordinates \( x_0 \) and \( y_0 \) are time dependent and the oscillation amplitude becomes to

\[
V(x, y, t) = \frac{A}{\sqrt{(x-x_0(t))^2 + (y-y_0(t))^2}} \quad \text{for} \quad \sqrt{(x-x_0(t))^2 + (y-y_0(t))^2} > R
\]

outside the sphere and

\[
V(x, y, t) = \frac{A}{2R} \frac{(x-x_0(t))^2 + (y-y_0(t))^2}{2R^3} \quad \text{for} \quad \sqrt{(x-x_0(t))^2 + (y-y_0(t))^2} \leq R
\]

inside the sphere, whereas

\[
V(x, y, t) = V(x, y, t + nT) \quad \text{for} \quad n = 1, 2, 3, \ldots \quad \text{with} \quad T = \frac{2\pi}{\omega_0}
\]

In the following only one-dimensional modulations with the modulation length \( L \) are considered and hence \( x_0(t) = 0 \). As examples from various kinds of modulations, linear and sinusoidal modulations are investigated more in detail.

2.1. Linear modulation

In the first example the electron beam is modulated locally with a periodic saw function:

\[
y_0(t) = \sum_{n=-\infty}^{\infty} g(t - nT) \quad \text{with} \quad g(t) = \frac{L}{T} \cdot t \quad \text{for} \quad -\frac{T}{2} \leq t < -\frac{T}{2}
\]

This leads to a distribution of the oscillation amplitude at the excitation frequency \( \omega_0 \) as simulated in figure 1. Here the parameters were \( L = 50 \mu m \) and \( R = 1 \mu m \) It behaves quite similar to the distribution of a normal line source.

2.1.1. Decay in far-field. The decay in the far-field perpendicular to modulation direction is calculated as follows. The oscillation amplitude is approximated by a power series.

\[
V(x, y, t) = \frac{A}{|x|} \left( 1 + \frac{(y-y_0(t))^2}{x^2} \right)^{-1/2} = \frac{A}{|x|} \left( 1 - \frac{1}{2} \left( \frac{y-y_0(t)}{|x|} \right)^2 + \frac{1}{2 \cdot 4} \left( \frac{y-y_0(t)}{|x|} \right)^4 - \ldots \right)
\]

For the far-field (\( x \to \infty \)) terms of higher orders after the second term can be neglected and thus the decay perpendicular to modulation direction in the middle of the modulation line becomes:

\[
V(x, y = 0, t) = \frac{A}{|x|} \left( 1 - \frac{y_0^2(t)}{2x^2} \right)
\]

\( y_0^2(t) \) is calculated by development of Fourier series:

\[
y_0^2(t) = \frac{L^2}{12} + \sum_{n=1}^{\infty} \frac{(-1)^n L^2}{n^3 \pi^2} \cdot \cos(n \omega_0 t)
\]
and the far-field oscillation becomes to:

\[
V(x, y = 0, t) = \frac{A}{|x|} - \frac{A \cdot L^2}{24 \cdot x^3} - \frac{A \cdot L^2}{2 \cdot x^3} \sum_{n=1}^{\infty} \frac{(-1)^n \cos(n\omega_0 t)}{n^2 \pi^2}
\]

This Fourier analysis shows that the dc part decays by \(1/x\) like a normal spherical dc source, whereas the oscillation components of \(\omega_0\) and higher harmonics decay locally by \(1/x^3\). This is stronger than the \(1/x\) far-field decay for a normal time-modulated line source, since in the far-field not only the amplitude, but also the modulation decreases. Hence, this source has an accentuated near-field.

![Figure 1](image1.png)  
**Figure 1.** Simulated spatial distribution of oscillation amplitude for linear modulation.  

![Figure 2](image2.png)  
**Figure 2.** Simulated spatial distribution of oscillation amplitude for sinusoidal modulation.

### 2.2. Sinusoidal modulation

Another way to modulate the electron beam is by a sinusoidal function:

\[
y_0(t) = \frac{L}{2} \sin(\omega_0 t)
\]

Figure 2 shows the local oscillation amplitude at \(\omega_0\) of a source modulated sinusoidally with the same geometrical parameters as in 2.1. It can be seen that the source characteristic of this modulation has two maxima at the ends of the modulation line whereas in the middle the signal is zero. In a first approach it can be treated as two point-like sources with a phase shift of 180°.

### 3. Experimental setup

![Figure 3](image3.png)  
**Figure 3.** Experimental setup of the acoustic ESEM/AFM hybrid system.
An AFM is built inside the chamber of an ESEM which gives the advantage of combining two microprobes [7]. Sample and tip have a tilt of 60° with respect to the electron beam so that the beam can excite the sample directly under the AFM tip. The electron beam is modulated locally by applying an additional voltage to the scan coils. Hence, acoustic waves are generated in the sample by electro-acoustic coupling. They lead to Surface Acoustic Waves (SAW) at the sample surface which can be detected in vertical as well as lateral direction with the AFM tip in contact mode by laser deflection with lock-in amplifiers.

4. Results

4.1. Source characteristics
To verify the local distribution simulated above, the vertical oscillation of a linear modulated source (20kHz) has been measured on a GaAs membrane. Figure 4 shows a line measurement orthogonal to the source at \( y=0 \) for three different modulation lengths \( L \). The measurements (markers) coincide quite well with the simulations (lines). The curves can be divided in three parts: inside the source \((R=10\mu\text{m})\), the near-field and the far-field. The near-field has a logarithmic decay, which is characteristic for acoustic line sources [6]. The width of the near-field increases with increasing modulation length, since linear properties of the source become more observable. This has also been shown for microscopic line sources in thermal mode [8]. Hence, the linear modulated source can be considered as an acoustic line source with respect to the amplitude in near-field.

![Figure 4](image1.png) **Figure 4.** Line scan of linear modulation perpendicular to modulation direction for different modulation lengths.  

![Figure 5](image2.png) **Figure 5.** Verification of the \( 1/x^3 \) decay in the far-field of linear modulation.

The far-field decay can be observed in figure 5 in detail, where a line measurement is displayed in a double-logarithmic graph. It shows that the measurement in far-field of the linear modulation is parallel to the \( 1/x^3 \) function which proves the decay characteristic calculated in 2.1.1.

4.2. Application to ferroelectric ceramics
As an example of application for this acoustic near-field technique, the detection of ferroelectric domains is performed on a BaTiO\(_3\) ceramic. Domain investigation has been performed by many different acoustic techniques [2-5] and hence it can verify the acoustic properties of this method. The acoustic wave generated by the electron beam is detected in the near-field with the cantilever. The local oscillations depend on the different domain polarizations since the elastic and piezoelectric

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constants in the material change with the polarization angle [9]. Scanning the sample and keeping source and tip constant, the domain distribution can be detected.

Figure 6 shows an experiment comparing linear and sinusoidal modulation of \( L = 43 \mu m \) at a frequency of 50.25kHz. In figure 6b) the tip was placed in near-field in the middle of the linear modulation which has been performed in parallel to the cantilever. During sinusoidal modulation (figure 6c)), which has been performed vertically to the cantilever to avoid interaction of the other maximum, the tip was placed in the near-field of one maximum. The quantitative lateral oscillation amplitudes are calculated according to [10].

![Figure 6](image)

**Figure 6.** Measurement on BaTiO\(_3\): a) topography and domain structures in lateral oscillation amplitude excited by b) linear and c) sinusoidal modulation.

In the acoustic images ferroelectric domain structures can be seen, where large domains (\(~4\mu m\)) consist of smaller domains (\(~0.5\mu m\)). For linear modulation, a clearly better contrast in the lateral oscillation signal is achieved. This can be explained by the directional acoustic emission of the line source, whereas at the maxima of the sinusoidal modulation the emission is non-directional. Hence, the in-plane oscillation of the sample is much higher for linear than for sinusoidal modulation. Advantages of these direction-dependent properties in the emission characteristic are that only acoustic properties in one dimension can be investigated, whereas the other dimensions are faded out.

![Figure 7](image)

**Figure 7.** Measurement of spatial resolution: a) topography, b) acoustic image and c) line measurement of b)

In figure 7 an area is shown where three different kinds of domain orientation come across. The acoustic image in figure 7b) was achieved under the same conditions as 6b). It is demonstrated that the spatial resolution of the acoustic image, which is determined by the cantilever as the smaller micro probe, is about 40nm.
5. Conclusion
A technique for local generation of acoustic waves in an SEM without beam blanker is demonstrated. It is shown that different source characteristics with different acoustic near-field properties can be achieved depending on modulation. Ferroelectric domains could be detected by using an AFM tip as local acoustic detector. A large advantage of this technique using two micro probes at the sample surface is its independence of sample geometries. Even thick samples can be investigated without problems of sample mounting and preparation or acoustic matching.

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