Keysight Technologies

Wideband Electrostatic Force Microscopy (EFM): Broad Frequency Range with High Sensitivity

Technical Note

Introduction

Various electrical atomic force microscopy (AFM) techniques are available that are capable of sensing the nanoscale electrical properties of samples ranging from 2D materials over silicon to those of biophysical interest. Electrical AFM modes can be distinguished by current/impedance sensing and force sensing techniques as shown in Figure 1, with each technique having their own advantage and operating frequency. Force sensing techniques (lower part in Figure 1) that rely on the optical readout of the cantilever deflection, like EFM (electrostatic force microscopy) and KFM (Kelvin force microscopy), are typically limited to the characterization of static or low frequency electric properties and quasi-static dielectric properties of up to 100 kHz. Current and impedance sensing techniques (upper part in Figure 1) where the electrical signal of the AFM cantilever is read out with an external electronic circuitry, for instance SMM (scanning microwave microscopy), can work from 1 to 20 GHz.

Here we introduce wideband EFM (described originally in Refs. 1,2 and further applications shown more recently in Refs. 3-6) that extends the available EFM frequency range from the kHz range to the GHz range, which allows for detection of the frequency dependent tip-sample impedance, Z(f). Compared to SMM, wideband EFM can also work below 1 GHz and with higher electrical sensitivity, but only the magnitude of the impedance Z can be measured. While SMM works in contact mode, EFM is operated in tapping or lift mode which reduces the tip wear and sample modifications. Compared to standard EFM, the higher frequency range of wideband EFM enables more measuring capabilities, including conductive properties.

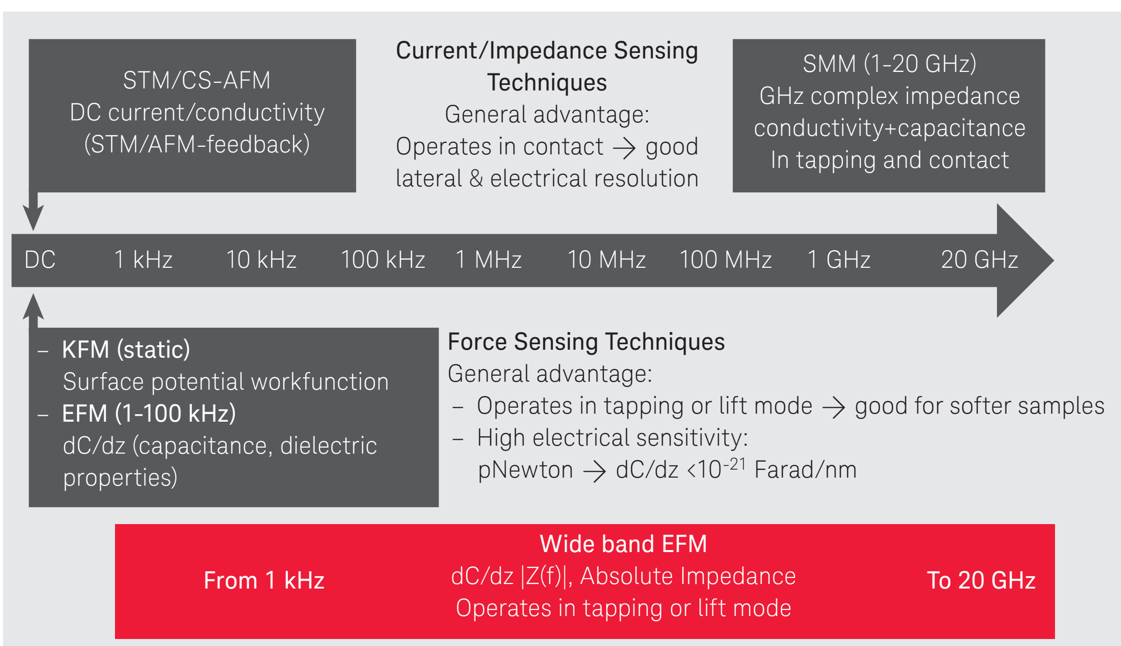

Figure 1. Electrical AFM techniques and their operating frequency range. SMM (scanning microwave microscopy); KFM (Kelvin force microscopy); EFM (electrostatic force microscopy); CS-AFM (current-sensing AFM).

Applications

Standard EFM is limited to characterization of quasi-static capacitive sample properties. Extended frequency range in wideband EFM allows for detecting frequency dependent dielectric as well as conductive properties. New insights can be acquired with this method, including the following:

- Local dielectric spectroscopy in a wide frequency range, together with conductive properties (for instance, how carrier mobility of 2D materials change with frequency)
- Sub-surface imaging of hard and soft materials with different electrical properties (e.g. silicon 3D devices)
- Investigation of dielectric properties in liquid environment based on the water dielectric constant and biomolecules hydration
- Electrical characterization of magnetic materials (permeability, ferro-magnetic resonance)
- Electrical characterization of semiconductors with reduced wear of the tip in lift mode.

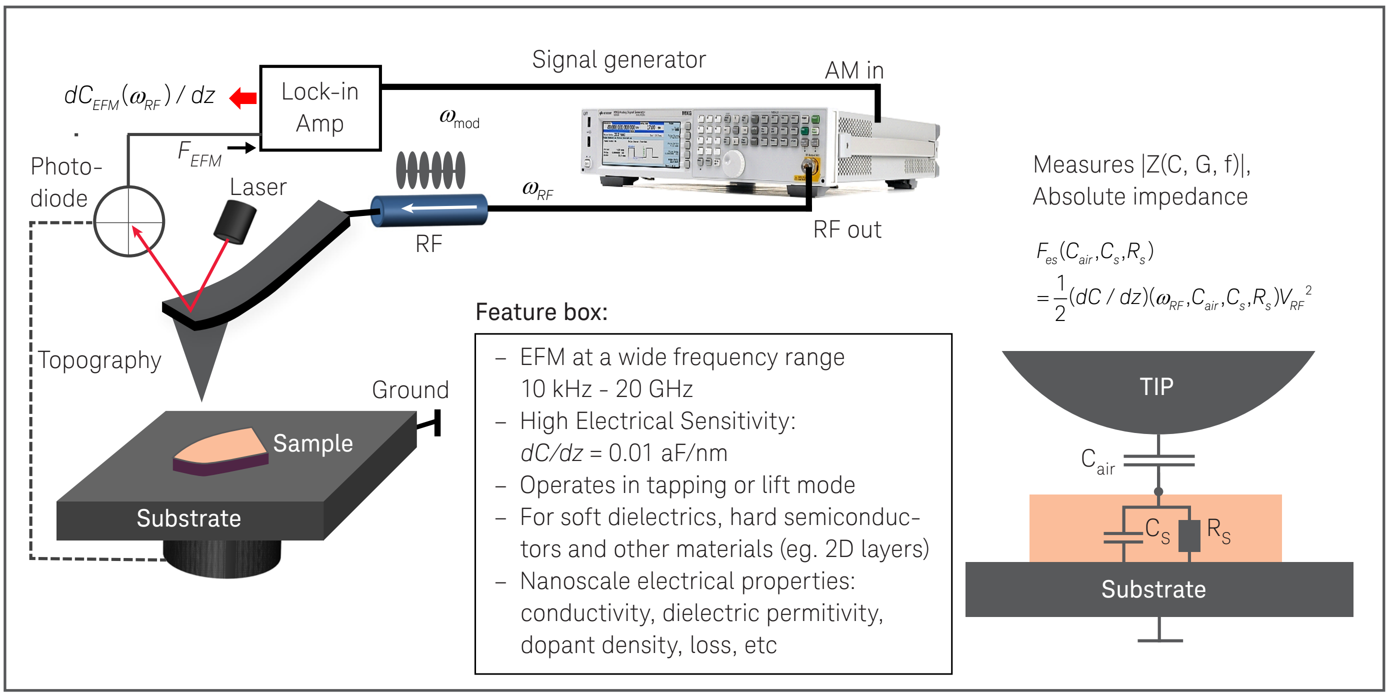

Figure 2. Wideband EFM setup. Left: The AFM is interfaced with a signal generator (Keysight MXG N5183B) which delivers an amplitude modulated signal to the conductive AFM probe. The tip holder of the AFM is designed to deliver electrical signals from DC up to 20 GHz to the probe, which is the same nose cone used in SMM. The cantilever starts to oscillate at the modulation frequency and detects the local complex capacitance of the sample as function of the carrier frequency. Right: Wideband EFM measures the electrostatic forces Fes at a given frequency ω_{RF} as a function of capacitance (C) and conductance (G). The circuitry model describes how Fes is correlated to the sample impedance.

Operation Principle

Wideband EFM works based on the attractive force that arises when applying a sinusoidal electric field between the conductive probe and the substrate. In standard EFM, the forces of the first harmonic, $\omega(KFM)$ and second harmonic, $2\omega(dC/dz)$ of the excitation signal are detected by a lock-in amplifier. Only low frequencies (below the mechanical resonance of the cantilever) can be measured, typically in the kHz range. However, the dc force component can also be used to measure the capacitance gradient, $dC/dz(\omega)$ thus electrical and conductive properties. In wideband EFM, the signal is down-converted to dc, therefore the measurement can be done in a wide frequency range from kHz to GHz which is well above the mechanical resonance of the cantilever. To increase sensitivity and accuracy, a heterodyne detection approach is applied based on the amplitude modulation of the high frequency signal (Figure 2). A signal generator with a high frequency range delivers a carrier signal with a frequency ω_{RF}, which is modulated by amplitude modulation (AM) at a much lower frequency, ω_{mod}. Due to the modulation, the cantilever starts to oscillate at the modulation frequency. This is detected by the AFM photodiode and the lock-in amplifier, giving information on the local complex capacitance gradient at ω_{RF}. The complex capacitance gradient dC^*/dz also varies with the resistive/conductive properties of sample as detailed in Figure 2. Selection of the carrier frequency ω_{RF} allows for estimation of capacitive and resistive properties of the sample under study.

A dielectric measurement of a biological membrane patch (bacteriorhodopsin, also known as “purple membrane” from Halobacterium salinarium) is shown in Figure 3. Single, double and triple layers of the membrane with a height of 5 nm to 15 nm are visible. The cell membrane mainly composed of protein has a dielectric constant of about 3 and is measured at a frequency of f=100 MHz.

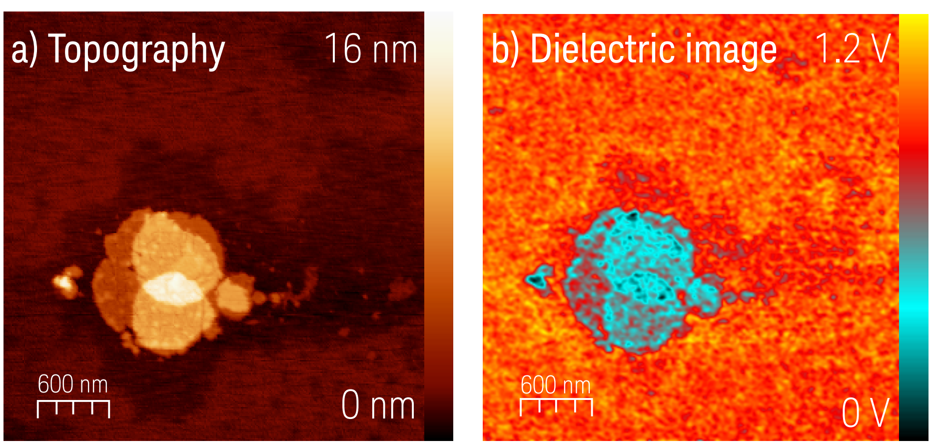

Figure 3. Dielectric measurement of purple membrane from Halobacterium salinarium on mica. a) AFM Topography b) Wideband EFM signal acquired in lift mode (10 nm lift height) at f=100 MHz.

References

1. Hou A et al., *Scanning probe microscopy for testing ultrafast electronic devices*. Opt. Quant. Electron. (1996) 28, 819-841
2. Leyk A et al., *Voltage Amplitude and Voltage Phase Mapping within sub-Âµm Devices by High Frequency Scanning Force Microscopy*. IEEE MTT-S Digest, (1996) 1525-1528
3. Gramse G et al., *Dynamic electrostatic force microscopy in liquid media*. Appl. Phys. Lett. (2012) 101, 213108
4. Umeda K. et al., *Direct actuation of cantilever in aqueous solutions by electrostatic force using high-frequency electric fields*. Appl. Phys. Lett. (2012) 101, 123112.
5. M. Labardi et al. *Local dielectric spectroscopy of polyvinylpyrrolidone–$Mo_6S_2I_8$ nanowire composite*. J. Non-Cryst. Solids (2013) 379, 224
6. Gramse G et al., *Nanoscale Measurement of the Dielectric Constant of Supported Lipid Bilayers in Aqueous Solutions with Electrostatic Force Microscopy*. Biophys J. (2013) 104, 1257-1262.

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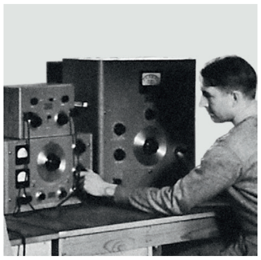
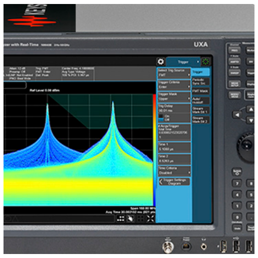


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