Developments and Recent Progresses in Microwave Impedance Microscope

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Abstract. Microwave impedance microscope (MIM) is a near-field microwave technology which has low emission energy and can detect samples without any damages. It has numerous advantages, which can significantly suppress the common-mode signal as the sensing probe separates from the excitation electrode, and it is a powerful tool to characterize electrical properties with high spatial resolution. This article reviews the major theories of MIM in detail which involve basic principles and instrument configuration. Besides, this paper summarizes the improvement of MIM properties, and its cutting-edge applications in quantitative measurements of nanoscale permittivity and conductivity, capacitance variation and electronic inhomogeneity. The relevant implementations in recent literature and prospects of MIM based on the current requirements are discussed. Limitations and advantages of MIM are also highlighted and surveyed to raise awareness for more research into the existing near-field microwave microscopy. This review on the ongoing progress and future perspectives of MIM technology aims to provide reference for the electronic and microwave measurement community.

1. Introduction
The past decade has witnessed efforts in the field of microwave to develop a near-field scanning microwave microscope (NSMM) as a scientifically powerful instrument with rapid development [1]. Early implementations of the microscope either used a small aperture at microwave cavities [2] or a needle-shape probe coupled to a microwave resonator [3,4]. Due to the hardship in tip-sample distance control, these approaches are intrinsically susceptible to tip damage and difficult in nanoscale quantitative measurement applications [5]. The microwave impedance microscope (MIM) can control tight distance perfectly and solve the crucial probe-sample gap control issue in the nanometer range NSMM. Moreover, it shows great advantages in reducing the loss in doped silicon traces while ensuring large power gain and high sensitivity because it employs metal lines for the electrodes and cancels background signal before amplification. In addition, the MIM can significantly suppress the common-mode signal since the inductive probe is separated from the excitation electrode [6,7]. Compared to atomic force microscopy (AFM) and scanning tunneling microscopy (STM), the long-range electrostatic force involved in scanning MIM reduces the stringent requirements for proximal probes, enabling high-speed, non-contact and non-destructive measurements [8,9]. Due to the aforementioned advantages, the MIM achieves near-field measurements at nanoscale and has great potential in future application of high-resolution microwave images generation.
In this review, we present a comprehensive study of development and recent progress in MIM. This review focuses on technique improvements and applications and covers MIM limitations and advantages, as well as the opportunities for further research into the subject of near-field measurement. The rest of this paper is organized as follows. Section II gives a brief history and an overview of the structure of MIM and discusses the fabrication process and improvement of MIM. Section III treats various cutting-edge applications. Section IV presents the conclusions and discussion.

2. Basic Design and Improvement of Scanning Microwave Impedance Microscopy

2.1. History and design of Scanning Microwave Impedance Microscopy

The employment of microwave frequency band has many advantages, such as strong penetration, the ability to detect the internal information of the sample, and the common polarization of short relaxation time by the frequency influence [10,11]. Scanning microwave microscopy (SMM) is a powerful tool for the investigation of various properties, including conductivity, permittivity, and impedance at the nanoscale. Different designs of resonant SMMs with very high sensitivity and spatial resolution have been demonstrated [12,13]. Despite the encouraging progress in SMMs, several limitations exist in current designs [14]. A case in point is the large common-mode signal, which results in loud noise. Slow operation and low bandwidth dampen the special effect of long-range force involved in a microwave microscope. Scanning microwave impedance microscopy (MIM) is a species of SMM [15,16]. MIM solves this problem successfully. Unlike traditional SMMs, MIM determines the electrical properties through the analysis of the phase and amplitude of the reflected wave instead of through frequency drift and quality factor change. The preponderance of this technique is that it shields the external signal and reduces the common mode signal. MIM was prominent in that the sensing probe was separated from the excitation electrode, while still maintaining high sensitivity and spatial resolution. The schematic construction of MIM was shown in Fig.1, in which the traditional tip is replaced with a standard AFM tip assembly and two transmission lines are included, one for excitation and the other for sensing. A two-layer implementation like this improves the system’s common-mode rejection ratio and reduces the noise level significantly. With a proper design, the detector can be “orthogonal”. Then the signal is minimized in the absence of a sample [17]. A high throughput near-field scanning microwave microscope can be implemented. Besides the sharp sensing electrode, a second electrode surrounding the tip is also present on the cantilever to significantly suppress the common-mode signal.

![Fig 1](image_url)

**Fig 1.** The schematic construction of MIM. (a) Micro fabricated microwave probe with two aluminum electrodes and the ground plane patterned on the Si nitride cantilever. (b) Schematic drawing of the layer structure near the probe end. (c) SEM image near the probe end. Reproduced with permission from Rev. Sci. Instrum. 79, 6 (2008). Copyright 2008 American Institute of Physics.
The lumped element circuit description is related to the representative probe, with three impedances $Z_e$, $Z_t$, and $Z_{et}$ as illustrated in Fig. 2. Since there is a large mismatch between $Z_t$ ($Z_e$) and the transmission line impedance $Z_0$ (50 Ω), the microwave power cannot be transmitted to the probe, and detecting a small microwave impedance variation is infeasible if the microwave power is directly connected to the feeder [18]. In order to improve the transmission of microwave power, it is important to achieve impedance matching. As shown in Fig. 2, the resonator is then critically coupled to the feed line by a parallel open-end tuning stub.

**Fig 2.** Impedance matching section. A λ/4 cable and a tuning stub (inside the dashed boxes) form the interface between the probe and the 50 Ω feed lines. Reproduced with permission from Rev. Sci. Instrum. 79, 6 (2008). Copyright 2008 American Institute of Physics.

The microwave is conducted into the tip through a directional coupler. Then it gets into the directional coupler after the surface reflection, and a cancellation signal is inputted to suppress background reflected signal at the same time. Reflection microwave signals and cancellation signals are amplified and demodulated to the quadrature mixer. Finally, the reflected signal consists of in-phase and out-of-phase components [19,20]. It contains information about the local permittivity (capacitance) and conductivity (resistance) of the sample.

**Fig 3.** Depiction of the experimental set up for MIM. Reproduced with permission from Appl. Nanosci. 1, 1 (2011). Copyright 2011. Springer Nature.

### 2.2. Improvement of Scanning Microwave Impedance Microscopy

In recent years, MIM has been developed to characterize the electrical properties of sample such as permittivity and conductivity. Accordingly, the need for MIM is increased. Many recent articles discuss the improvement of MIM in sensitivity, resolution and wideband.

A compact mode microwave impedance imaging based on an atomic force microscope platform was proposed [21]. Tap mode microwave imaging was also superior to contact mode because thermal drift and other electron drift observed in contact mode can be completely eliminated and absolute measurements of dielectric properties can be made. [22] the authors reported the design and fabrication of a piezo resistive cantilever with a low-impedance conduction line to our electrically-shielded tip. Their new design exhibits vertical displacement resolution of 3.5 nm in a measurement bandwidth from 1 Hz to 10 kHz. The probes provide topography feedback with nanometer vertical resolution for samples or setups where laser detection is not feasible or desirable. Furthermore, the low parasitic impedance of
the tip enables MIM measurements. The self-sensing cantilever allows topography feedback where the laser beam bounce technique is not available or hard to implement. This probe will enable coupled topography scans with MIM images. A novel fabrication in a GaN nanowire probe for near-field scanning microwave microscopy was suggested and investigated [23], with improved sensitivity and reduced uncertainty achieved which can measure capacitance values down to as small as 0.7 fF while simultaneously recording 10 nm height changes.

Y. Yang reported novel batch-processed low impedance, well-shielded and sharp tips piezo resistive cantilever probes for simultaneously topographical and electrical scanning probe microscopy. High quality piezo resistive topography and MIM images are simultaneously obtained with the fabricated probes [24,25]. These novel piezo resistive probes remarkably broaden MIM applications in scientific and engineering studies of new materials and electronic devices by operating photosensitive samples with an integrated feedback mechanism at low temperatures.

Fig 4. $S_{11}$ image with four different probes indicates a minimum sensitivity. (a) Scan results for Ti/Al NW probe over DUT showing change in the amplitude of the microwave reflection coefficient $S_{11}$. All micro-capacitors are present in the image, indicating sensitivity to at least 0.7 fF. (b) $S_{11}$ image with a bare NW probe indicates a minimum sensitivity of 3 fF. (c) $S_{11}$ image with Si probe indicates a minimum sensitivity of 6 fF. (d) $S_{11}$ image with Pt probe indicates a minimum sensitivity of 0.7 fF. All scans are plotted with different Z-axis color scales for clarity. All micro-capacitors are present in the image, indicating sensitivity to at least 0.7 fF. Reproduced with permission from Appl. Phys. Lett. 104, 2 (2014). Copyright 2014 American Institute of Physics.

The design and performance of a fully integrated CMOS-MEMS SMM were presented by M. Aziz in detail. The block diagram of the entire SMM system includes the tip of the sample being tested, the SMM device fabricated using CMOS-MEMS technology, the matching network and the measurement
circuit 60. In this case, an increase in sensitivity means that for a given tip-sample impedance change, the change in system output (\( V_{\text{out}} \) or \( S_{11} \) in Fig.5) will be maximized. These experiments confirmed the potential of SMM to reveal features not detected by AFM.

Fig 5. Block diagram of the SMM system.

3. Cutting-edge application of mim
MIM is a quantitative near-field tool [26,27] that operates at a high-frequency GHz range 28. It can detect the electrical properties of various samples and implement microwave detection technology at macro/nano scale, showing broad application prospects. MIM has made rapid progress. Recent applications of MIM are summarized in this section.

3.1. Quantitative Measurements of Nanoscale Permittivity and Conductivity
The dielectric constant of materials including high-k insulators can be quantitatively measured and the author measured the approximate curve of an oscillating tip toward bulk dielectric samples using the MIM. The approximation curve of the MIM-C channel output can be accurately described by lumped element FEA simulation using standard locking techniques [28].

Fig 6. Peak MIM-C signal in tip-sample approaching as a function of the relative dielectric constant. Reproduced with permission from Appl. Phys. Lett. 93, 12 (2008). Copyright 2008 American Institute of Physics.

X.Wu developed TF-MIM by using drive amplitude modulation (DAM) mode, which provides satisfactory stability for samples with rough surfaces. The demodulated MIM AC signal was simulated...
by combining the finite element analysis (FEA) of the leading sample admittance with the Fourier transform of the real-time signal [29,30]. This work shows that TF-MIM is an effective tool for quantitative nanoscale imaging of electrical properties in functional materials.

Fig 7. Demodulated tip-sample admittance and the corresponding MIM-Im AC signals as a function of the relative permittivity. Re-produced with permission from Rev. Sci. Instrum.89, 4 (2018). Copyright 2018 American Institute of Physics.

3.2. Capacitance Variation
H. Huber proposed a calibration method that can be widely applied to SMM based on the study of quantitative measurement of dielectric contains of thin films using SMM [31,32]. And calibration procedures for nanoscale capacitance measurements allows quantitative assessment of material and device performance in SMM measurements. Customized standard samples, coupled with end-to-end interaction modeling and thorough PNA data processing, make it possible to calibrate SMM parameters, including calibration capacitance and effective probe size.

Fig 8. AFM-tip/sample capacitance and effective tip radius. (a) Topographical image of the bare 10 nm stepped dielectric staircase structure. (b) Corresponding PNA amplitude image with the different
steps resolved (0 dB corresponds to the bare silicon surface, as seen at the far right edge of the image). (c) The PNA amplitudes were converted to capacitances and plotted with respect to the x-coordinate of the white line in (b). (d) For each dielectric step, the capacitance was determined using an area analysis and subsequent averaging of the PNA amplitude. Reproduced with permission from Rev. Sci. Instrum. 81, 11 (2010). Copyright 2010 American Institute of Physics.

3.3. Electronic Inhomogeneity

B. Yu reported the observation of electronic inhomogeneity in indium selenide (In$_2$Se$_3$) nanoribbons by near-field scanning MIM [33,34]. Microwave probes compatible with atomic force microscopy enable quantitative sub-surface electronics research in a non-invasive manner. The large signal with opposite signs recorded by the MIM most vividly displays the phase change memory function of the In$_2$Se$_3$ devices. It is possible to further implement the MIM as a spatially-resolved readout instrument for memories with great resistivity changes. The author demonstrates that the MIM can provide spatially resolved information when In$_2$Se$_3$ nano-devices are phase-switched by voltage pulses.

Fig 9. Simultaneously taken topography and MIM-C images of an In$_2$Se$_3$ nanoribbon. Reproduced with permission from Nano Lett. 9, 3 (2009). Copyright 2009 American Chemical Society.

4. Conclusions

Near-field microscopy at microwave frequencies has attracted many research interests in the past decades [35,36]. MIM expands the scope of local electrical characteristics testing. The MIM based on microwave detection mainly uses microwave as the detection source and obtains the information of the tiny electrical parameters in the sample microregion in combination with probe technology [37]. The MIM probe is microfabricated on a silicon nitride cantilever with a shielded metal trace and a Pt tip deposited by a focused ion beam (FIB) [38]. Therefore, we believe that MIM can provide a powerful and versatile tool to study nanoscale dielectric inhomogeneities in a non-invasive manner. This paper reviews developments and recent progress in MIM and discusses both MIM limitations and advantages, as well as the opportunities for further research into the subject of near-field measurement. This paper also seeks to raise awareness regarding the need for more research into the existing near-field microwave microscopy in order to address the limitations of MIM.

However, the geometry of the tip is limited to a few specific types. The finished nib is almost impossible to have a strictly regular shape in practice. For near-field microscope in the microwave state, few theoretical works focus on specific designs presented. As with any artifact, due to the disturbance caused by the probe, the measurement component of the microwave signal and the image deconvolution have not been attracted much attention to. With the development of microwave near-field microscopy, these voids will be filled in time. At the same time, the preparation of the scale and the durability of the probe are long-term topics.
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