

Characterization of Dielectric Nonlinearities in High-k Materials in Active mmW Devices

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Mission-critical wireless services such as radar systems, 5G networks, and space-based communications demand high-performance electronic components capable of operating at millimeter-wave (mmW) frequencies and handling significant power levels. Central to these advancements are mmW transmitters, phased arrays, and high-power devices based on wide bandgap (WBG) semiconductors like Gallium Nitride (GaN) and Aluminum Gallium Nitride (AlGaN). To further enhance the performance of these devices, thin-film high-k dielectric materials, such as Barium Titanate (BaTiO_3) and Titanium Dioxide (TiO_2), are incorporated into the transistor topologies as gate insulators. These materials improve breakdown voltages, device gain, power output, and operating frequencies while reducing the size, weight, and power (SWaP) requirements for integrated systems. Understanding the dielectric permittivity and loss tangent characteristics of these materials under high electric fields is thus critical for designing and fabricating such high-power transistors. This knowledge is pivotal for performance optimization, enabling better energy efficiency and higher operating speeds. Moreover, precise characterization under high electric fields provides significant advantages for system-level design, unlocking superior performance in mission-critical applications.

In this study, we present a method to characterize the non-linear behavior of BaTiO_3 thin films under varying electric field intensities, using an on-wafer fixture for permittivity and loss tangent characterization. The proposed fixture is a multilayer coplanar waveguide (CPW), as shown in Fig. 1, fabricated via patterning copper metallization on a semiconductor substrate. To demonstrate the efficacy of the on-wafer fixture, the CPW structure is patterned on an RF-sputtered BaTiO_3 layer of $\sim 250\text{nm}$ thickness, grown on a high-resistivity Silicon (HRSi) substrate. The gaps of the CPW allow for direct application of high electric fields using a Vector Network Analyzer (VNA) with an internal bias tee to deliver the DC bias through one of the probes, as illustrated in Fig. 2. This fixture leads to in-plane electric fields in the kV/cm level. By applying the permittivity extraction procedure in (Y. Ozturk, B. Paul, A. Arage, N. K. Nahar and K. Sertel, "Characterization of Automotive Paint Permittivity for mmWave Radar Applications," *IEEE Transactions on Microwave Theory and Techniques*, vol. 72, no. 4, pp. 2477-2485, Apr. 2024), we demonstrate a simple and effective method of characterizing the complex relative permittivity of the thin BaTiO_3 films under high electric fields at mmW frequencies. The details of the on-wafer calibration and permittivity extraction procedure along with measurement data will be presented at the conference. The proposed approach can also be applied to characterize other high-k dielectric thin films used in nanofabrication as well as electronic packaging, such as TiO_2 , and can be extended to higher frequency bands to enable future high-power THz transistors.

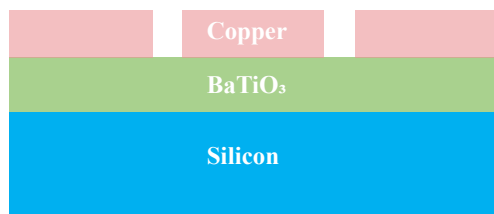


Figure 1. Multilayer CPW topology for BaTiO_3 characterization under high DC electric fields.

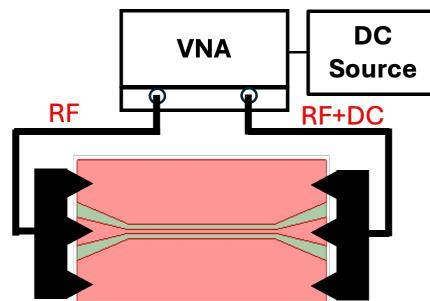


Figure 2. Proposed measurement fixture based on a probe station and a VNA with internal DC bias tee.