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► **To cite this version:**

Srikanth Kolagatla, Sombel Diaham, Paul Lambkin, Ricky Anthony, Megan Mccarthy, et al.. Electrostatic Force Microscopy Technique for Understanding Failures in Polyimide Insulation Barriers. ISTFA 2024, Oct 2024, San Diego, France. pp.460-462, 10.31399/asm.cp.istfa2024p0460 . hal-04850231

HAL Id: hal-04850231

<https://hal.science/hal-04850231v1>

Submitted on 19 Dec 2024

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Electrostatic Force Microscopy Technique for Understanding Failures in Polyimide Insulation Barriers

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Abstract

Inductive Coupling technology has replaced the conventional optocoupler due to their performance, size, and power consumption advantages. One of the critical part in these devices is the polyimide acting as isolation barrier. The characteristic failure modes of this polyimide layer includes high voltage breakdown at the edges. Here, a systematic study characterizing polyimide of different thickness at different DC biases charge injections is performed using Electrostatic Force Microscopy (EFM) in air. Correlating the injection charge and dissipation time with respect to layer thickness helps in identifying the right barrier thickness thereby reducing the failures at product level.

Introduction

Digital isolators have been widely adopted for safe signal and power isolation in automotive, industry automation, medical, and energy sectors, due to their high speed, low power consumption, high reliability, small size, high integration, and ease of use [1]. One of the critical components in digital isolators for high voltage application is the insulation layer which can be a polymer such as polyimide or inorganic layer such as silicon nitride or an oxide. Polyimide (PI) being an electrical insulator is widely used in microelectronics devices due to its thermal, chemical, and mechanical stability. Also, PI can form thick isolations (> 50 μm) with multiple spin coating processes [2, 3].

The isolation properties of PI are affected by several variables including thickness, area, interfacial electrodes, and environmental conditions [2-4]. It is of critical importance to understand properties of polyimide in high voltage environments. An important property of insulating materials is their ability to accumulate charges under electrical stress. Even though this effect is useful for some applications, charge injection and accumulation in dielectric layers remain the main cause of failure in many devices. Figure 1 shows the breakdown of polyimide film at high voltages on a test structure. To overcome this drawback a deep understanding of the mechanisms leading to charge injection and storage mechanism close to the metal / dielectric interface injection area with a very high resolution is critical.

Atomic Force Microscopy (AFM) because of its sensitivity to electrostatic force and its high resolution can characterize charges at nanoscale. Amongst different electrical modes in

AFM, electrostatic and kelvin probe force microscopy (EFM/KPFM) have shown a significant promise towards characterizing the charge storage capability and charge injection mechanisms of dielectric materials such as silicon nitride layer and other polymer insulators [5-7]. In this work, a study of charge injection and dissipation at metal/dielectric interface at high local electric fields over time using EFM technique on polyimide layers with different thickness is demonstrated.

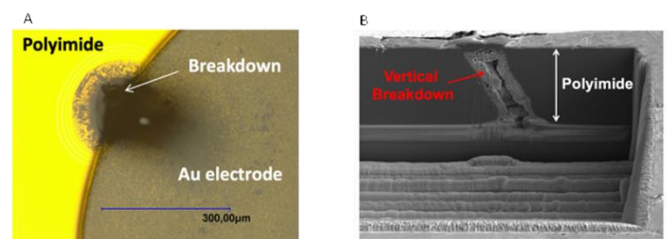


Figure 1: Polyimide breakdown at high voltage: (A) Optical microscope top view image of Polyimide breakdown on a test device, (B) SEM cross section image of polyimide breakdown region.

Experimental

A commercial AFM system (Park systems NX20 wafer scale AFM system) was used in this study. Pt/Ir-coated conductive probes (PPP-EFM) supplied by the vendor, with nominal tip radius < 15 nm, resonant frequency of 75 kHz, and a spring constant of 2 N/m were used for both topography and EFM measurements. Charge injection measurements were performed in contact mode, where the tip is scanned in a raster pattern over a 5 μm scan region with a defined DC bias. These measurements were repeated on polyimide sample with thickness ranging from 5 μm - 20 μm . The EFM scanning was performed in single pass mode in air, in which the topography of the surface is obtained from the mechanical resonance of the probe while simultaneously applying an AC voltage $V_{ac} \sim 2 \text{ V}$ at 17 kHz to the tip generating an electrostatic force between the tip and the sample which helps with monitoring the injected charges. Each topography and EFM map consisted of 256 * 256 pixels. Figure 2 shows experimental illustration of charge

injection into polyimide film and schematic illustration of EFM technique (park systems).

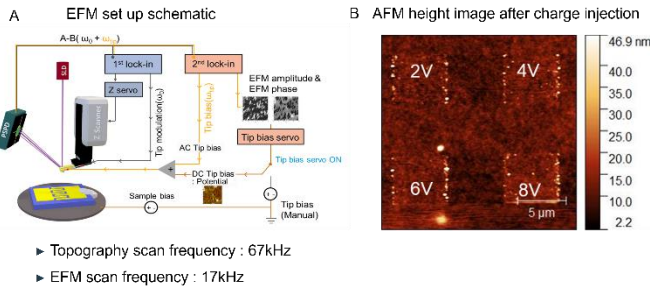


Figure 2:(A) EFM experimental schematic (park systems), (B) AFM height image after charge injection into polyimide film.

Experimental results and discussion

In this work, we systematically characterized the charge injection capabilities of polyimide film at different thickness. From these measurements we identified how the injection rate differs at different potentials with respect to the change in the thickness. The charge relaxation time is also calculated at different potentials. Figure 3 show the EFM charge injection measurements done on 5 μm polyimide film. AFM topography image of polyimide film is shown in Fig 3(A) and its corresponding EFM amplitude image is shown in Fig 3(B). The Charge injection measurements were performed on the polyimide film using contact mode where the tip is scanned in a raster pattern over a 5 μm scan region at a scan rate of 1 Hz with DC bias applied to the probe, the DC bias values are 2 V, 4 V, 6 V and 8 V respectively. Fig 3(C) shows the topography image of the polyimide surface after charge injection, a clear marking of the charge injected regions is visible. Fig 3(D) shows the EFM amplitude image of the surface after the charge injection measurements. Clear differentiation is observed between the charge injected region and unbiased regions. The

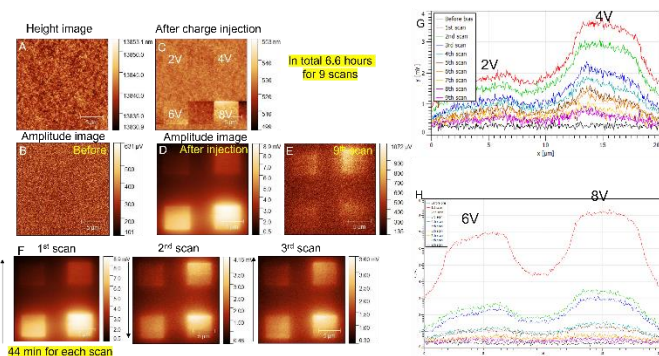


Figure 4: Charge injection measurements on 5 μm polyimide film. (A) AFM topography image of polyimide film before charge injection (B) EFM amplitude image (C) AFM topography image after charge injection (D) EFM image after charge injection (E) EFM scan after completed dissipation of injected charges (F) EFM amplitude images of different scans (G, H) EFM profile images of different scans at different biases.

charge injection was higher with increase in DC bias. The amplitude profiles of charge dissipation at different scans is shown in Fig 3(G, H). The charge injection profiles show the EFM amplitude change measured at different potentials, at 2 V the measured amplitude is 2 mV and similarly for 8 V it's 8 mV this shows a liner behavior. The total amount of time it took for

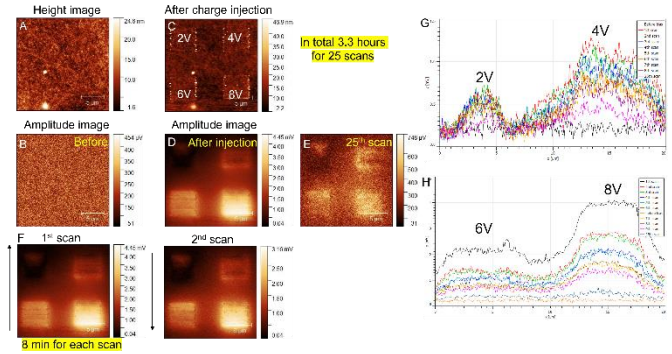


Figure 3: Charge injection measurements on 10 μm polyimide film. (A) AFM topography image of polyimide film before charge injection (B) EFM amplitude image (C) AFM topography image after charge injection (D) EFM image after charge injection (E) EFM scan after complete dissipation of injected charges (F) EFM amplitude images of different scans (G, H) EFM profile images of different scans at different biases.

the complete discharge of all the injected charges is around ~ 396 minutes. Figure 4 shows the charge injection measurements on a 10 μm thick polyimide film. Fig 4(A) shows the AFM topography image of polyimide film before injection and its corresponding EFM amplitude image is shown in Fig 4(B). Fig 4(C) shows the topography image of the polyimide surface after charge injection at 2 V, 4 V, 6 V and 8 V. Fig 4(D) shows the EFM amplitude image of the surface after the charge injection measurements. The profiles of charge dissipation at different scans is shown in Fig 4(G, H). At 2 V the measured amplitude is 0.7 mV which is ~95% decrease in the charge injection at this potential when compared with 5 μm thick polyimide. Similarly,

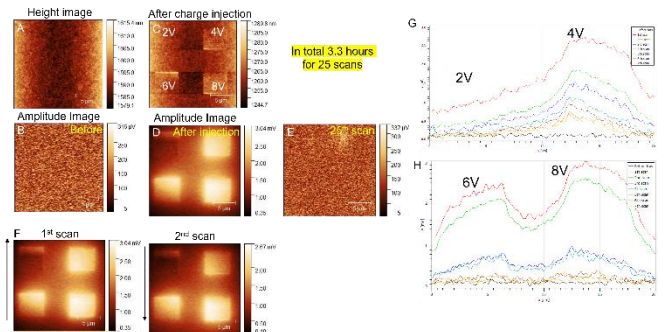


Figure 5: Charge injection measurements on 20 μm polyimide film. (A) AFM topography image of polyimide film before charge injection (B) EFM amplitude image (C) AFM topography image after charge injection (D) EFM image after charge injection (E) EFM scan after complete dissipation of injected charges (F) EFM amplitude images of different scans (G, H) EFM profile images of different scans at different biases.

for 8 V it's 4 mV which amount to ~66 % decrease in charge injection. The total amount of time it took for the complete discharge of all the injected charges is around ~195 minutes which is almost half the time for a complete discharge on a 5 μm thick polyimide sample.

Figure 5 shows charge injection measurements on 20 μm thick polyimide film. Fig 5(A) shows the AFM topography image of polyimide film before injection and its corresponding EFM amplitude image is shown in Fig 5(B). The charge injection was minimal at 2 V, the charge injection at this bias was not well defined as the other higher biases, there is an uneven distribution over the injected region as shown in Fig 5(D). The measured EFM amplitude value at 2 V was 0.7 mV which is similar to 10 μm thick sample. Similarly, for 8 V it's 3 mV which amount to ~28% decrease in charge injection. The total amount of time it took for the complete discharge of all the injected charges is ~195 minutes which is similar to the 10 μm polyimide surface.

Conclusions

In this work, the charge injection and dissipation on different thick polyimide films was studied using EFM technique. The polyimide film showed no morphological degradation when applied with different DC biases. The charge injection measurements at different polyimide thickness shows that higher the bias the more injection happened and at 5 μm thickness it's almost linear, taking almost ~360 minutes for it to discharge. At 10 μm thick polyimide film the amount of charge injected was almost reduced to half, which is a significant property to consider. Simultaneously it also took half the time to completely dissipate the charge. At 20 μm polyimide thickness the charge injection didn't take place at 2 V bias and at higher biases the charge injection is almost similar to 10 μm polyimide thickness. This shows that after a certain thickness level the charge injection and dissipation is do not change. Even though the DC voltage applied is significantly smaller to what is used in the isolation devices, these experimental results shows that polyimide retains charges for significant amount of time and the thickness of polyimide places a critical role in defining the effective behavior as well as failure time for the inductive isolator device.

Acknowledgements

This work was supported by a research grant from Science Foundation Ireland (SFI) under the SFI Industry fellowship Award Grant Number SFI/22/IRDIFB/10997.

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