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High-Field and High-Frequency Dependencies of Intrinsic Dielectric Properties and Lifetime in Polyimide at Sub-PDIV

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Abstract—Standard accelerated lifetime tests on industrial parts such as polyimide-based digital isolators are usually performed under 60 Hz AC in a range below the partial discharge inception voltage (PDIV). However, new applications such as EV electrical motors fed by power inverters with fast power devices (i.e. SiC, GaN) and controlled with pulse-width modulation (PWM), involve higher working frequencies, potentially ranging up to 100 kHz with very high $dV/dt \gg 10$ V/ns. It is therefore important to know whether such conditions can impact the electrical reliability of polyimide. To establish the combined effects of high field and high frequency, a comprehensive investigation has been undertaken. It firstly assessed both the intrinsic properties of polyimide films at high voltage and high frequency in the sub-PDIV range. In addition, accelerated endurance experiments on fully built packaged units, also at higher frequency in square wave (50 kHz) were performed and are reported here.

Keywords—Digital isolator; Polyimide; Electrical insulation; AC Breakdown; High Frequency; High voltage endurance; Lifetime.

I. INTRODUCTION

Polyimide (PI) is an excellent insulating material used in high voltage (HV) engineering [1]. It is widely used in the electronics industry to manufacture reliable digital isolators (DIs) with both high working voltage (>600 V_{rms}) and surge rating ($\gg 10$ kV) in addition to high partial-discharge inception voltages (PDIV >3 kV_{rms}) [2-4]. DIs have a wide range of applications including industry 4.0, isolated-gate drivers for electric vehicles and medical electronics for health monitoring. In some of these applications, such as motor drive control by pulse-width modulation (PWM), the trend is to increase the switching frequency beyond 10 kHz [5]. This is motivated by rescaling the power system (i.e., using smaller, and lighter transformers, filter inductors and capacitors), as well as increasing the overall efficiency. Consequently, the operating frequency of isolated-gate drivers has increased and so the PI insulating barrier used in DIs must also now support the electric field stress at these elevated frequencies [6-8].

Before release to the marketplace, DIs must demonstrate conformity to regulatory standards. As such, high voltage endurance (HVE) tests, performed at 60 Hz, are a requirement. From these the working voltage condition is estimated using admitted

electrical lifetime models [9]. However, with new opportunities in the field of power converter control, it is important to assess any negative impact on the lifetime and working voltage for devices (operating below PDIV) resulting from the elevated frequencies and electric field.

To date, the effects of high frequency on electrical aging of PI insulation have mainly been reported in the high voltage range above PDIV, i.e., where the lifetime integrity during the HVE test is severely degraded due to an extrinsic PD-driven erosion process. For instance, this is observed for enameled wires used in HV electrical motor windings when accelerated electrical aging is performed above PDIV on twisted pairs [10]. In contrast, for DI applications where the HVE tests and the extrapolated working voltage are all performed below PDIV (i.e., at sub-PDIV), a PD-driven degradation process might appear as irrelevant. If further high frequency electrical aging does exist, it might originate from more intrinsic sources (e.g., dielectric heating) that are still compatible with the used lifetime models.

Electrical aging effects on PI DIs, specifically in sub-PDIV conditions, is poorly reported, due likely to unreasonable HVE test durations. The aim of this paper is to fill this gap by considering the combination of high field and high frequency. Firstly, by demonstrating the intrinsic impact on PI films when they are exposed to high-frequency, intense electric fields whilst voltage is maintained below PDIV. Secondly, by investigating the aging response of the dielectric properties with frequency.

II. EXPERIMENTAL

A. Material and Test Structures

The polyimide was prepared from a polyamic acid solution (PAA), precursor of a pyromellitic dianhydride (PMDA) and an oxydianiline diamine (ODA) dissolved in an *N*-methyl-2-pyrrolidone (NMP) solvent.

Samples were prepared on an industrial production line inside a high-class clean room facility. The PAA solution was spin-coated onto 8''-diameter Si wafers with a top PECVD oxide layer that, in turn, supported a bottom electrode (TiW/Au/TiW). The top surface of the film was subsequently deposited with an electroplated TiW/Au metal. The test structures were finally encapsulated with a thicker capping PI layer to suppress corona discharges. For the intrinsic dielectric characterization, a PI thickness of about 6 μ m after

thermal curing was used. Circular capacitor test structures were patterned by photolithographic processing (see Figure 1).

On the other hand, for HVE and lifetime testing, micro-transformer device test units with bottom and top coils separated by a 30 μm thick PI barrier were processed on the same principal but then assembled into a package using a standardized molding compound.

B. Intrinsic Dielectric Testing at Wafer-Level

The intrinsic dielectric properties characterization involved: (i) high voltage broadband dielectric spectroscopy (HVBDS) to extract the AC conductivity (σ_{AC}) versus the electric field and frequency; and (ii) high frequency AC breakdown voltage (HFBDV) to measure the breakdown field (E_{BR}) versus frequency.

The HVBDS measurements were made using a Novocontrol broadband dielectric analyzer coupled to a high-voltage HVB-4000 boost module supplying AC voltages up to $\pm 2 \text{ kV}_{pk}$ in a frequency range from 100 mHz up to 10 kHz.

High-frequency AC breakdown testing was carried out using a high voltage Trek amplifier ($\pm 30 \text{ kV}_{pk}$) controlled with an arbitrary waveform generator that supplied AC ramp voltages with frequency between 60 Hz up to 10 kHz. Tests involved immersing the wafer-level samples in fluorinert oil to prevent surface discharges and to ensure an intrinsic type of failure. For statistical analysis, a total of 20 samples was tested for each frequency.

All the tests were performed at room temperature and after a pre-conditioning at 150 $^{\circ}\text{C}$ for 48 h in an oven.

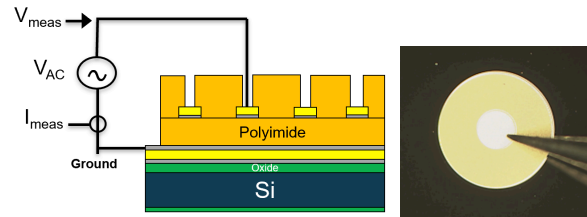


Fig. 1. Cross-section sketches (a) and top view picture (b) of the PI circular MIM capacitor wafer-level test structures used for intrinsic dielectric characterization.

C. HVE Testing on Packaged Units

High-frequency accelerated endurance tests were performed on packaged units. To evaluate the frequency effects on lifetime, a total of 16 tested packaged units were electrically aged for each frequency at a given voltage. The multiple units were mounted in parallel on burn-in boards placed in ovens with controlled atmospheric conditions (25 $^{\circ}\text{C}$, 40% RH) and further connected to an in-house power supply that delivers a $\pm 2 \text{ kV}_{rms}$ bipolar square wave voltage ($dV/dt = 40 \text{ V/ns}$, 50% duty cycle) in a frequency range up to 50 kHz. A switch/measurement unit was used to individually monitor the time-to-

failure for each part. For comparison, lifetime was evaluated under standardized 60 Hz sinewave HVE test conditions.

III. RESULTS AND DISCUSSION

A. High-Field & High-Frequency AC Conductivity

Figure 2a presents the frequency dependency of the AC conductivity of PI films for various applied electric fields. Below 100 $\text{V}/\mu\text{m}$, the AC conductivity remains field-independent and follows the universal Jonscher's power law, confirming a pure and linear dipolar orientation process. However, with stronger electric fields, the slope tends to decrease monotonically whilst the AC conductivity begins to increase and become nonlinear.

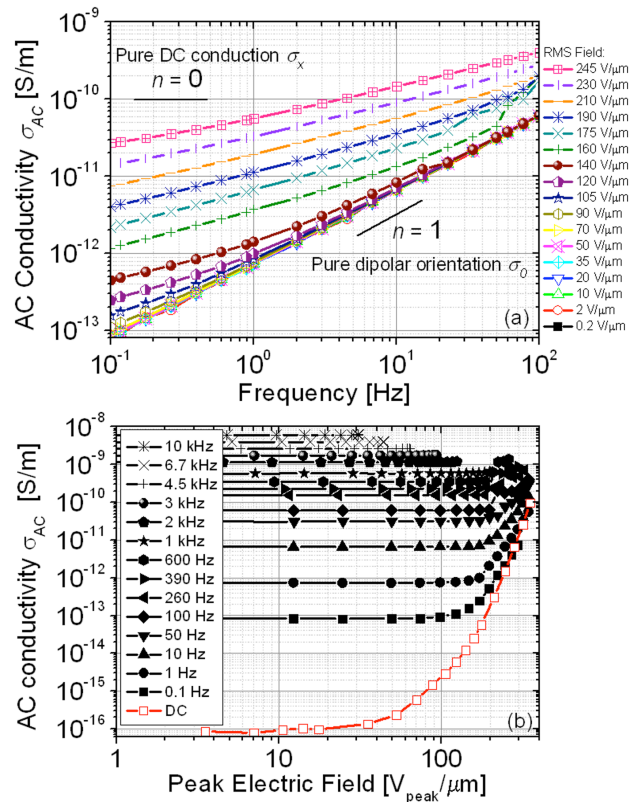


Fig. 2. Frequency (a) and electric field (b) dependencies of the AC conductivity σ_{AC} in PI films.

Figure 2b replots the AC conductivity of the PI films (including the DC component) as a function of the peak electric field and for different frequencies. It clearly demonstrates that the nonlinear DC and AC conductivities converge indicating partly common conduction mechanisms (injection and space charge) above a certain electric field threshold. At high frequency, this electric field threshold occurs at a peak field above 100 $\text{V}/\mu\text{m}$.

B. Power Dissipation

From these measurements, the dielectric power loss density P_d has been calculated and is plotted in

Figure 3 based on Eq. (1) [11] in the map format as a function of electric field and frequency:

$$P_d = \omega \epsilon_0 \epsilon'' E^2 \quad (1)$$

where ω is the angular frequency, ϵ_0 the vacuum permittivity (8.854×10^{-12} F), ϵ'' the imaginary part of the permittivity ($\sigma_{AC} = \omega \epsilon_0 \epsilon''$) and E the applied electric field.

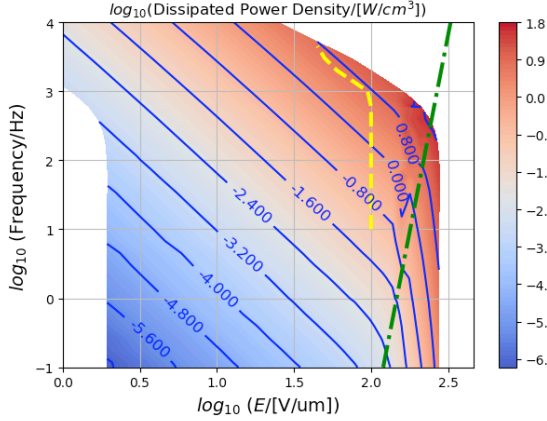


Fig. 3. Dissipated power density with rms electric field E , and frequency f . The dot-dashed line indicates the contour at which the nonlinear component of loss equals that of the linear contribution. The region to the left of the dashed line is where the power dissipation response is linear, that includes the safe working E-fields and frequencies in applications.

The measured region is divided between a linear and nonlinear response by the dashed contour. To the ‘left’ of this line the power dissipation increases both with applied E-field and frequency, as expected. In contrast, in the nonlinear region, the dependence on frequency is much reduced and the applied field is the dominant parameter. For many applications, linearity is of utmost importance and is a key criterion for long term, reliable HV insulating performance of PI films. This implies that in high voltage service conditions at 60 Hz, as well as at least up to 10 kHz, the electric field applied on PI film should not exceed $80 \text{ V}_{\text{rms}}/\mu\text{m}$ throughout the insulated device to reap the benefits of the highest reliability.

C. High-Frequency AC Breakdown

Figure 4 shows the Weibull statistics of the rms breakdown electric field of the PI film measured at different frequencies. Independent of the frequency, the breakdown field of the PI occurs at high values $>480 \text{ V}_{\text{rms}}/\mu\text{m}$, underlining the quality of the fabrication process. This value in the upper range for AC breakdown documented in the literature [12]. Moreover, the breakdown distribution data is tightly scattered. This emphasizes that the material processing, with all the industrial precautions, is well controlled and reproducible. This is supported by high values of the form factor β in the Weibull distribution. It is noted that during the tests PD-current was probed simultaneously (not shown here) to ensure that no

partial discharges occurred prior to the breakdown. Therefore, in the present case, the breakdown mechanism was not assisted by any PD degradation.

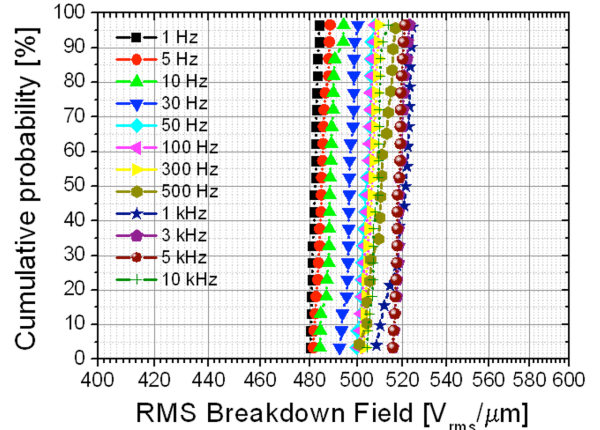


Fig. 4. Weibull distribution of the AC breakdown field for PI MIM capacitor structures at different frequencies.

To further analyze the frequency impact on the dielectric strength, the breakdown field at 63.2% (i.e., the scale factor) is replotted as a function of frequency in Figure 5. This plot shows the short-term AC breakdown to be independent of frequency in a range up to 10 kHz. In contrast, when breakdown occurs above PDIV, the result is usually frequency-dependent due to the high repetition rate of the discharges. Here a sub-PDIV breakdown (or PD-free regime) highlights that the underlying failure mechanism is likely the same, regardless of the frequency.

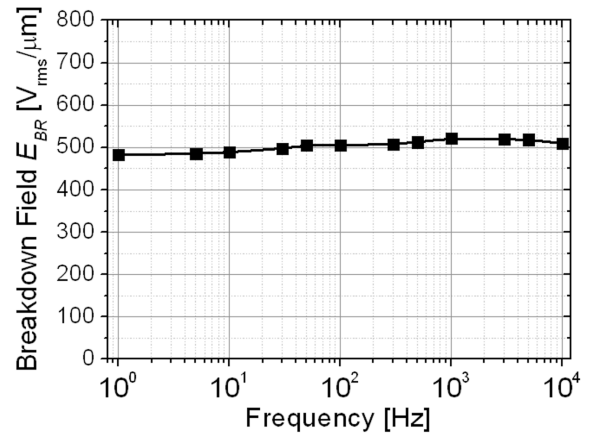


Fig. 5. AC breakdown field at 63.2% of the Weibull statistics for PI MIM capacitor structures.

D. High-Frequency Square Wave HVE and Lifetime

Finally, to evaluate the effects of frequency on long term electrical aging of PI, high frequency HVE tests were carried out on production packaged units that comprise microtransformer coils separated by a $30 \mu\text{m}$ PI insulating barrier. Moreover, to address electrical motor control applications fed by power converters working under pulse width modulation, the high frequency endurance tests were performed under high dV/dt square wave voltage until the entire population failed.

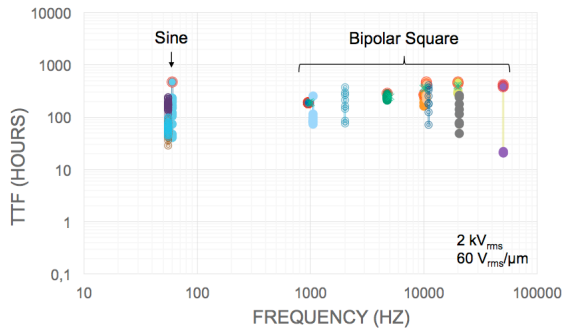


Fig. 6. Time-to-failure of packaged units (30 μm polyimide) versus frequency in bipolar square voltage at 2 kV_{rms} for various preconditions (lots, temperature and relative humidity). A comparison with standard HVE tests in AC voltage at 60 Hz is also plotted.

Figure 6 presents the time-to-failure (TTF) of polyimide packaged DIs versus frequency under bipolar square voltage measured at 2 kV_{rms} . Considering a combination of high electric field (60 $\text{V}_{\text{rms}}/\mu\text{m}$) with high frequency (up to 50 kHz here), such accelerated aging experiments show TTF is approximately identical over the investigated frequency range. This supports the observation that PI lifetime might not be affected by frequency when operated below the nonlinear AC electric field threshold. When comparing with standard HVE tests in AC sine voltage at 60 Hz, the high frequency TTF data are even marginally better.

Based on the multiple electrical analyses in this study, it appears that when the electric field is kept below the identified nonlinear conduction threshold of PI (80 $\text{V}_{\text{rms}}/\mu\text{m}$), the insulation integrity of the devices is maintained at high frequency. This study also shows that in accelerating aging conditions performed at more than $3\times$ the working electric field conditions, the lifetime is weakly dependent on frequency, at least up to 50 kHz under high dV/dt square voltage. Considering this latter point, it is unlikely that frequency can have a negative impact at working voltage conditions. Ongoing experiments, at lower voltages, are still running, designed to add further support for this statement.

IV. CONCLUSION

This paper aimed to correlate PI film intrinsic dielectric properties with its electrical reliability under combined high-field and high-frequency. Intrinsic HV broadband dielectric characterization has been performed whilst keeping the bias voltage below the PDIV with respect to digital isolator applications. Moreover, accelerated aging tests were performed in high dV/dt bipolar square voltage to assess the frequency impact on lifetime. The main conclusions of this study are that below PDIV:

- the AC breakdown strength of polyimide film is frequency-independent up to 10 kHz,
- the time-to-failure of packaged units at 2 kV_{rms} in bipolar square wave is frequency-independent up to 50 kHz,

- the high-frequency intrinsic wafer-level testing and the high-frequency package-level endurance testing show good correlation.

To date, current investigations indicate that the working voltage of polyimide insulating barriers can be immune to high frequency subject to operation below PDIV.

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REFERENCES

- [1] S. Diahm, "Polyimide in Electronics: Applications and Processability Overview", Chapter 1 in "Polyimide for Electronic and Electrical Engineering Applications", (Ed. S. Diahm, InTechOpen, London, UK, pp. 294, 2021).
- [2] B. Chen, J. Wynne and R. Kliger, "High speed digital isolators using microscale on-chip transformers", *Elektronik Magazine*, 2003.
- [3] S. Diahm, L. O'Sullivan, E. Ceccarelli, P. Lambkin, J. O'Malley, J. Fitzgibbon, B. Stenson, P.J. Murphy, Y. Zhao, J. Cornett, A. Sow, B. Chen, and S. Geary. "Improving Polyimide Isolation Performance by Tailoring Interfaces with Nitride Layers for Digital Isolator Application." IEEE 3rd International Conference on Dielectrics (ICD), July 2020.
- [4] B. Chen and S. Diahm, "Polyimide Films for Digital Isolators", Chapter 6 in "Polyimide for Electronic and Electrical Engineering Applications", (Ed. S. Diahm, InTechOpen, London, UK, pp. 294, 2021).
- [5] K. Shirabe, M. Swamy, J.-K. Kang, M. Hisatsune, Y. Wu, D. Kebort, J. Honea, "Advantages of high frequency PWM in AC motor drive applications", Proc. IEEE Energy Conversion Congress and Exposition (ECCE), 2012.
- [6] K. Mainali, S. Madhusoodhanan, A. Tripathi, K. Vechalapu, A. De, S. Bhattacharya, "Design and evaluation of isolated gate driver power supply for medium voltage converter applications", Proc. IEEE Applied Power Electronics Conference and Exposition (APEC), 2016.
- [7] B. Zhao, H. Qin, X. Nie, Y. Yan, "Evaluation of isolated gate driver for SiC MOSFETs", Proc. IEEE 8th Conference on Industrial Electronics and Applications (ICIEA), 2013.
- [8] R. Wu, J. Chen, N. Liao, X. Fang, "On-chip transformers with shielding structures for high dV/dt immunity isolated gate drive", Proc. IEEE Energy Conversion Congress and Exposition (ECCE), 2016.
- [9] L.A. Dissado, G. Mazzanti, G. Montanari, "The Incorporation of Space Charge Degradation in the Life Model for Electrical Insulating Materials." IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 2, No. 6, pp. 1147-1158, 1995.
- [10] Y. Yan, G. Wu, "Lifetime of Polyimide under Repetitive Impulse Voltage", Chapter 11 in "Polyimide for Electronic and Electrical Engineering Applications", (Ed. S. Diahm, InTechOpen, London, UK, pp. 294, 2021).
- [11] W. Wang, X. Wang, J. He, Y. Liu, S. Li and Y. Nie, "Electric stress and dielectric breakdown characteristics under high-frequency voltages with multi-harmonics in a solid-state transformer", Int. J. Electr. Power Energy Syst., Vol. 129, 106861, 2021.
- [12] S. Diahm, S. Zelmat, M.-L. Locatelli, S. Dinculescu, M. Decup, and T. Lebey, "Dielectric breakdown of polyimide films: Area, thickness and temperature dependence", IEEE Transactions on Dielectrics and Electrical Insulation, vol. 17, No. 1, pp. 18-27, 2010.