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In-package measurements of Space-Charge Accumulation in epoxy mold compound through Silicon Integrated Charge Sensors

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***Abstract*—The space charge dynamics in Epoxy Molding Compounds (EMCs) is critical for the reliability of high-voltage integrated circuits, especially under wet conditions. This work presents a novel approach for monitoring negative space charge accumulation in EMCs using integrated p-channel silicon charge sensors. The sensors, embedded underneath the EMC layer, allow for real-time detection of electrostatic potential variations by tracking changes in the sensor drain current. A calibration procedure based on the Enz-Krummenacher-Vittoz model enables conversion of the measured current into voltage, thereby quantifying the potential at the EMC/passivation interface. Experimental results under dry and wet conditions demonstrate that moisture significantly enhances EMC conductivity and accelerates charge transport. Additionally, the study shows that negative charge accumulation is slower than positive one, offering new insights into the charge transport mechanisms within EMCs. This method provides a promising tool for assessing high-voltage integrated circuits in-package reliability.**

***Index Terms*—Electronic Packaging, Epoxy-mold compound, space charge**

I. Introduction

In modern power electronic systems, the reliability and performance of high-voltage integrated circuits (HV-ICs) are critically influenced by the properties of the materials used in their packaging [1]. Recently, Epoxy Molding Compounds (EMCs) have emerged as the standard choice for encapsulating semiconductor devices due to their excellent mechanical properties, thermal stability, and cost-effectiveness in large-scale manufacturing [2]. They are polymers composed mainly of epoxy resins, hardeners, flame retardant and a large fraction of inorganic fillers such as silica or alumina [3]. This allows to achieve a very high dielectric strength [4], low ionic impurity content, and reduced moisture permeability while matching the thermal expansion coefficient of the silicon die. Thus, they are essential to provide protection against environmental stresses such as moisture, mechanical shocks, and chemical corrosion, ensuring the long-term robustness of electronic components [5] [6]. However, despite these advantages, the presence of space charge within EMCs remains a significant concern, particularly under harsh operating conditions, including high electric fields and elevated humidity levels. The space charge can distort the electrostatic potential distribution, compromising the insulation properties and ultimately leading to premature device failure [7]. A key challenge in addressing such reliability issues lies in the accurate characterization of the dynamics of space charge accumulation and its impact on device performance. Although the Pulsed Electro-Acoustic (PEA) method can achieve spatial resolution on the order of a few micrometers [8], this is typically limited to one-dimensional sample geometries and requires a highly sophisticated measurement setup, restricting its applicability in HV-ICs with complex structure. Recent advancements in test structures and simulation methodologies have provided new tools to investigate the charge dynamics in geometries that more closely resemble those found in high-voltage integrated circuits (HV-ICs). For instance, dedicated test chips integrating charge-sensor arrays have been developed to directly measure positive space charge accumulation at the EMC/passivation interface under both dry and wet conditions [9] [10]. The sensors, typically realized as gateless field-effect transistors, enable real-time monitoring of charge dynamics by detecting changes in the channel conductivity induced by the electrostatic potential distortion on top. Such approaches, together with conductivity measurements on interdigitated capacitors, have revealed that moisture absorption in EMCs can lead to a substantial increase in leakage currents and alter the electric field distribution, posing a significant risk to device reliability [11] [12]. Building on the latter developments, this work introduces a complementary study using silicon integrated p-channel charge sensors embedded underneath the EMC layer to monitor negative space-charge accumulation, providing complementary insights into the charge transport mechanisms within EMCs. By comparing charge dynamics under dry and wet conditions, this research aims to elucidate the role of moisture in EMC degradation and its implications for HV-IC reliability.

II. Device Structure and Experimental setup

The EMC under investigation is a commercial biphenyl/multi-aromatic resin with 88 wt% spherical silica filler. In order to measure the electrostatic potential in

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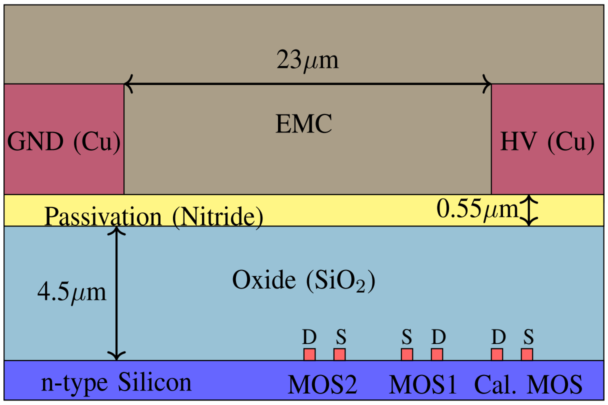

Fig. 1. Schematic representation of the test structure under investigation. Not to scale. If charge injection in to the EMC occurs, negative charges accumulate close to EMC/passivation interface and enhance the hole density in the channel of MOS1 and MOS2 leading to a time dependent current flowing through the drain and source contacts which are labelled as D and S, respectively. On the contrary, the hole density in the calibration MOSFET channel is fixed by the bias applied to the HV electrode.

the EMC, and thus gain physical insight into the space charge distribution within the sample, custom-designed test chips have been used. As shown in Fig. 1, the structure features two charge sensors, each implemented as long-channel, gate-less silicon transistors with shallow-trench isolation (STI) in both the channel and lateral extension regions. A nitride-rich silicon nitride layer is deposited above the sensors, followed by the integration of high-voltage (HV) and ground (GND) bond pads embedded within the EMC. A third transistor fabricated using the same masks as the sensors was incorporated under the HV contact, which can be used as a gate terminal, to directly characterize the transistor turn on characteristic. The n-type silicon substrate is equipped with a bottom electrode which serves as a body contact and can be used to tune the threshold voltage of the sensors. When a negative DC bias is applied to the HV electrode, in the case of an ideal insulator, the electrostatic potential within the EMC would be determined solely by the solution of the Poisson equation over the domain of the structure. The peculiar distribution of the electrostatic potential would lead to a large value of the electric field along both the horizontal and vertical directions [10]. If the vertical component of the electric field is sufficiently strong, it can induce the formation of a hole channel at the silicon/oxide interface within the substrate. Under these conditions, applying a negative bias between the drain and source contacts allows a hole current to flow. However, in the presence of leakage due injected charges from the electrodes, a time-dependent potential can be observed. More specifically, an electron injected from the HV contact will moves through the EMC to reach the GND contact. However, instead of flowing uniformly inside the EMC it would be confined close to the EMC/passivation interface due to the vertical component of the electric field. This accumulation of negative charges within the EMC contributes to the formation of the inversion layer in the channel of the underlying sensors, resulting in an increase of the sensor current. This phenomenon will continue until the electron concentration at the EMC/passivation interface will be sufficiently large to neutralize the vertical component of the electric field. Thus, by experimentally driving the HV electrode, the evolution of the electrostatic potential can be experimentally investigated, by directly measuring the drain current transient. All samples were initially placed in a thermostatic oven at 100°C for 48h to remove pre-existent humidity, thus obtaining dry reference samples. Subsequently, a subset of the dried devices was placed in a climatic chamber 85°C with a relative humidity of 85% for one week to allow controlled water absorption, reach humidity saturation, and thus obtain the corresponding wet samples. A Keitheley 2290-5 5kV power supply has been used as high voltage DC voltage source to polarize the EMC. The drain and body voltages have been fixed to -1V and -0.2V by using two different Agilent E3630A DC power supply, respectively. The current flowing through the sensors has been measured as function of time using Keysight B2981 A Picoammeters. All measurements have been performed at T = 300K.

III. Results

The i(t) curves of MOS1 and MOS2 measured on dry and wet samples for V_{HV} = 1500V and 1800V are reported in Fig. 2. Each measurement has been performed on three different samples. The observed sample-to-sample variability can be attributed to the random distribution of fillers, with typical dimensions of few μm, inside the sample which may affect the electrical properties of the EMC. To convert the current into the corresponding electrostatic potential at the EMC/passivation interface, it is necessary to determine a function that maps current values to voltages. This requires to compuete the inverse of the $I_D(V_G)$ characteristic obtained from the calibration sensor. Fig. 3 shows the measured $V_G(I_D)$ relationship together with the corresponding analytical approximation which has been derived using a simplified version of the Enz-Krummenacher-Vittoz (EKV) model [13]. It reads:

$$V_G = 2\dot{V}_T \cdot log\left(exp\left(\sqrt{\frac{I_D}{I_S}}\right) - 1\right) + V_{T0} \qquad (1)$$

where V_G is the equivalent gate voltage, I_D is the measured drain current, V_T is the thermal voltage, I_S is the specific current which depends on the geometrical parameter of the transistor, gate oxide capacitance and charge carrier mobility, and V_{T0} is the threshold voltage of the MOSFET. In the following, V_T, I_S, V_{T0} have been considered as three independent fitting parameters to better emulate the behaviour of the sensors. Once the current-voltage relation is calibrated, the dynamics of electrostatic potential in the EMC, due to space charge accumulation under DC bias, can be extracted from the drain current measured for both MOS1 and MOS2. Results are reported in Fig. 4 and show that an increase of the voltage experienced by the sensors can be observed by increasing V_{HV}. Moreover, the time needed by the system to achieve the steady state condition is reduced for larger stress biases. This can be

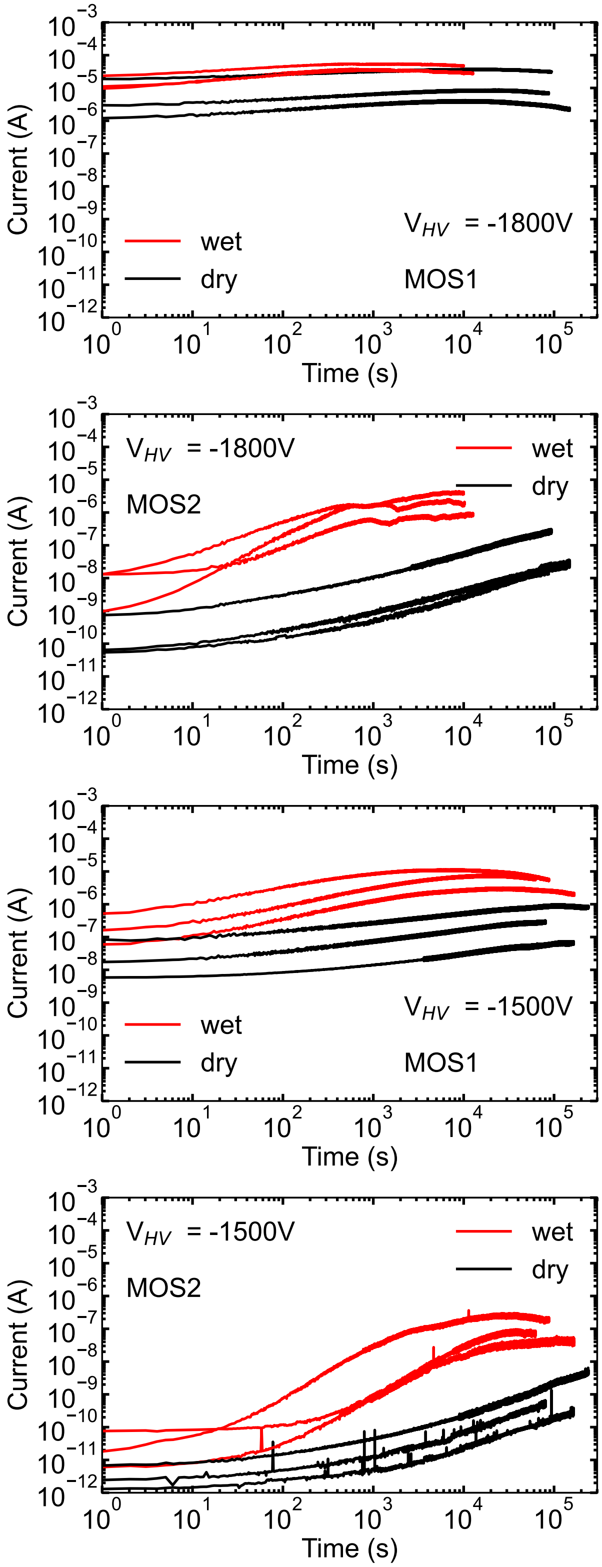

Fig. 2. Measured currents flowing through MOS1 (left) and MOS2 (right) as function of time for two different value of the DC stress bias V_{HV}. Black and red curves correspond to measurements performed on dry and wet samples, respectively.

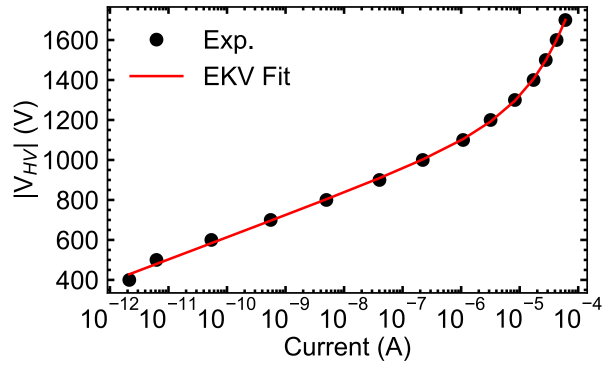

Fig. 3. $|V_{HV}|(I_D)$ curve extracted from the calibration MOSFET. Symbols: experiments. Solid line: fitting performed using the analytical expression for the gate voltage reported in Eq. 1.

ascribed to the increased velocity of charge carriers with the applied electric field. It is worth noting that the voltage remains constant for a certain period before exhibiting a significant increase. This delay may be associated with the time required to the negative charge injected from the electrode to migrate towards the portion of the EMC/passivation interface region above MOS1 and MOS2. By comparing results on dry and wet samples it can be concluded that the presence of moisture leads to an increase of the EMC conductivity. In Fig. 5, the average time needed to achieve the steady-state condition at $|V_{HV}| = 1500V$ is compared with previous results on n-channel sensors [10]. It can be observed that negative charges are significantly slower than positive ones. This observations demonstrate that, in the EMC, the transport of charge carriers has asymmetric behaviour and underline the necessity of an accurately modelling of the distinct dynamics of negative and positive charges.

IV. Conclusion

This study introduces a novel methodology for analysing negative space-charge accumulation in EMCs using embedded p-channel silicon sensors. By using the EKV model to convert the measured current into an equivalent gate voltage, it is possible to quantitatively extract the electrostatic potential at the EMC/passivation interface. The experiments revealed that increased bias voltage accelerates reduces the time needed to achieve a steady-state condition, while moisture absorption leads to enhanced EMC conductivity. These findings not only confirm the significant role of humidity in influencing EMC behavior but also highlight the slower transport dynamics of negative carriers compared to positive ones. The proposed approach provides a powerful diagnostic tool for evaluating the reliability and insulation performance of EMC-based HV-IC packaging under real-world conditions.

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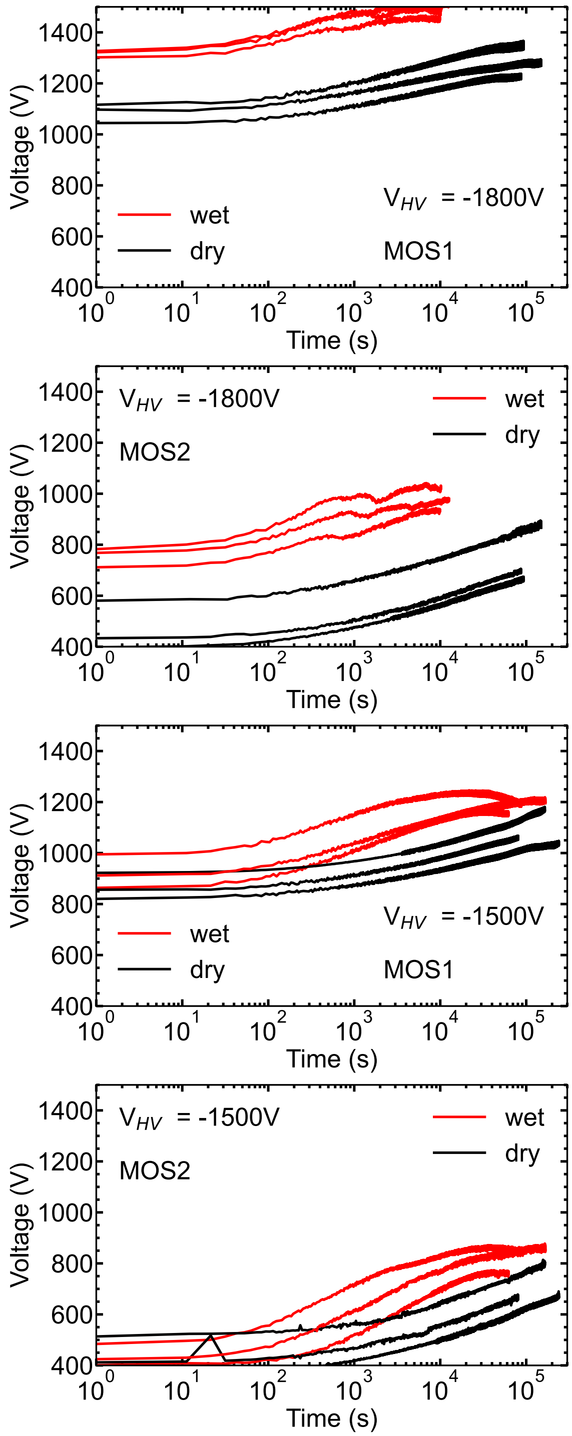

Fig. 4. Equivalent gate voltage on MOS1 (left) and MOS2 (right) as function of time for two different value of the DC stress bias V_{HV}. Black and red curves correspond to measurements performed on dry and wet samples, respectively.

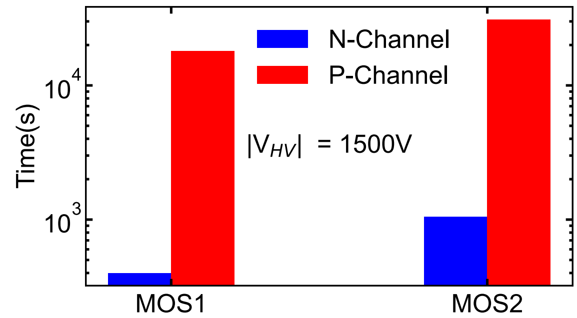

Fig. 5. Time required to reach steady-state conditions at $V_{\mathrm{HV}} = \pm 1500\,\mathrm{V}$ evaluated for both p-channel and n-channel charge sensors. It has defined as the time for the voltage to reach 99% of its steady-state value, with data for n-channel devices extracted from [10].

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