Chapter

Behavior of Space Charge in Polyimide and the Influence on Power Semiconductor Device Reliability

Kunihiko Tajiri, Hirotaka Muto, Didier Marty-Dessus, Laurent Berquez, Gilbert Teyssedre, Marie-Laure Locatelli, Sombel Diaham, Virginie Griseri and Flora Carrasco

Abstract

Polyimide is widely used in film form as a passivation material for power semiconductor devices such as Si, SiC, and GaN. The magnitude of the electric field at the edge termination area of these semiconductor devices is becoming higher due to the increase of operational voltage and/or demand for shrinking the edge termination area to increase device active area. Hence, it is concerned that the accumulation of space charge in the encapsulation and passivation material may affect the insulation performance of these devices, for example, the degradation of withstand voltage due to distortion of the internal electric field caused by space charge accumulation. To design space charge resistance of semiconductor devices, it is important to understand the space charge behavior in polyimide films with a thickness of several to several tens of micrometers. This chapter addresses practical implementation, specifications, and issues on space charge in polyimide insulation on power semiconductor devices focusing on the space charge measurements in thin polyimide films using the latest developed LIMM method and DC conductivity measurements.

Keywords: power electronics and devices, power modules, power semiconductor device, passivation material, space charge, LIMM, DC conductivity

1. Introduction

In recent years, high voltage electronics and power electronics applications have emerged needing the use of power semiconductor devices with widely used Si and wide bandgap materials such as SiC and GaN. In these devices, thin polymer material has been widely used as passivation coating to protect device surfaces. Particularly, polyimide (PI) is of great interest due to its excellent thermal and electrical properties and its easy processing. Some of the most important applications of these material films are as inter-level dielectric insulators and as electronic device surface passivation [1]. The typical image of PI layer at the edge surface of semiconductor chip is shown in **Figure 1**.

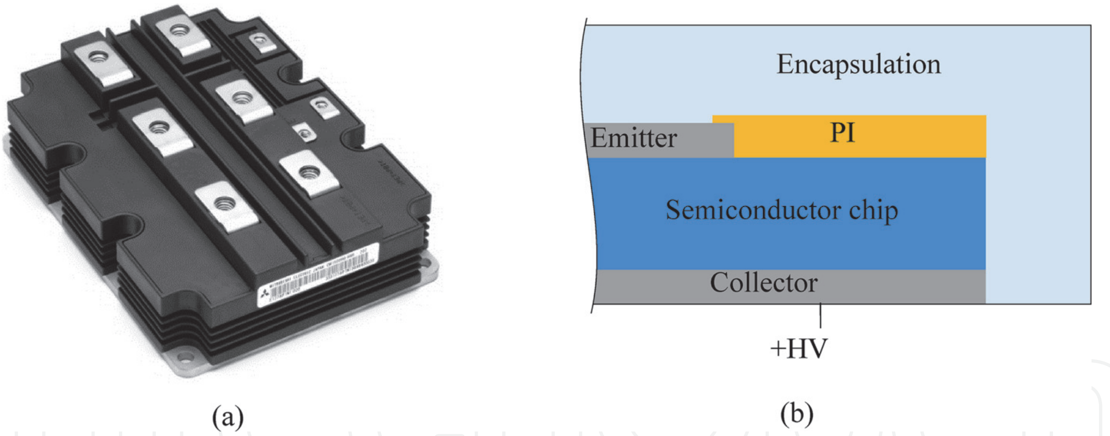

Figure 1.
Power module and edge termination structure of semiconductor chip. (a) HV IGBT power module. (b) Edge termination structure of semiconductor chip

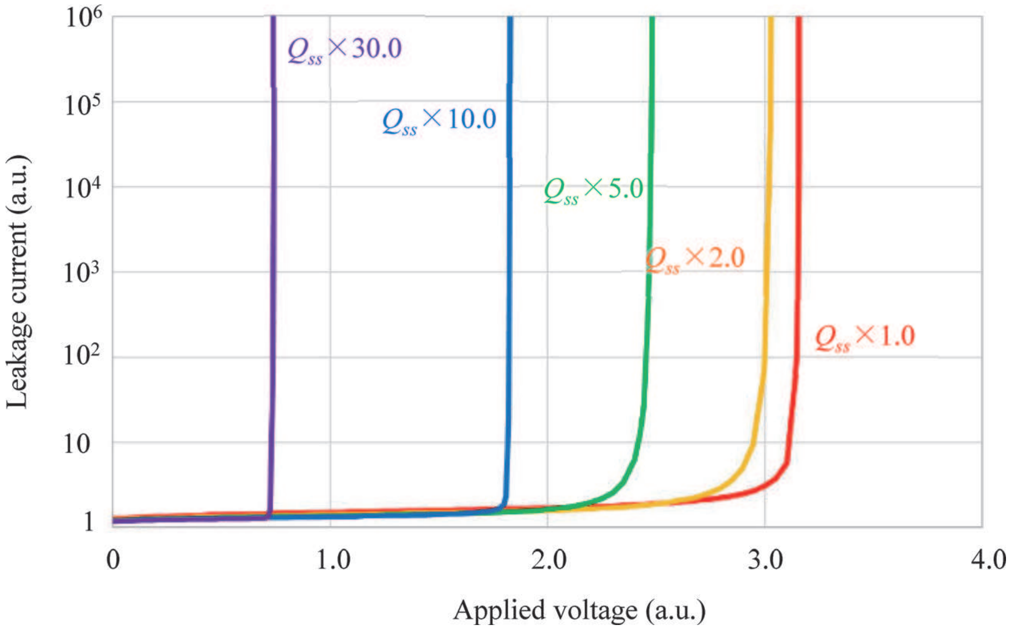

Figure 2.
Avalanche voltage simulation results of HVIGBT chip for different Q_{ss}.

Space charge is generally reported as a triggering mechanism for the degradation of insulators [2] and considered as a cause of the decrease of electrical breakdown voltage of those polymer films. Furthermore, the space charge could degrade semiconductor leakage current characteristics by strengthening the electric field in semiconductor substrate region. The influence of space charge transportation and accumulation on surface of semiconductor chip has been discussed in [3–6] using TCAD simulation. Reliability tests of IGBT devices under accelerated conditions were reported in [7, 8], showing that the degradation (increase) of leakage current of the device is caused possibly by the formation of space charge on the surface at semiconductor edge termination area. The decrease of withstand voltage of HV IGBT due to accumulated space charge (Q_{ss}) on the surface of device edge termination area has been demonstrated by TCAD simulation as shown in **Figure 2**. Attempts have also been made to evaluate the space charge resistance of a real chip by evaluating the withstand voltage of a semiconductor chip using a guard probe electrode to simulate an external electric field due to space charge as shown in **Figure 3** [9].

To evaluate the actual influence by the space charge accumulation, it is necessary to clarify the space charge distribution around the edge termination area of

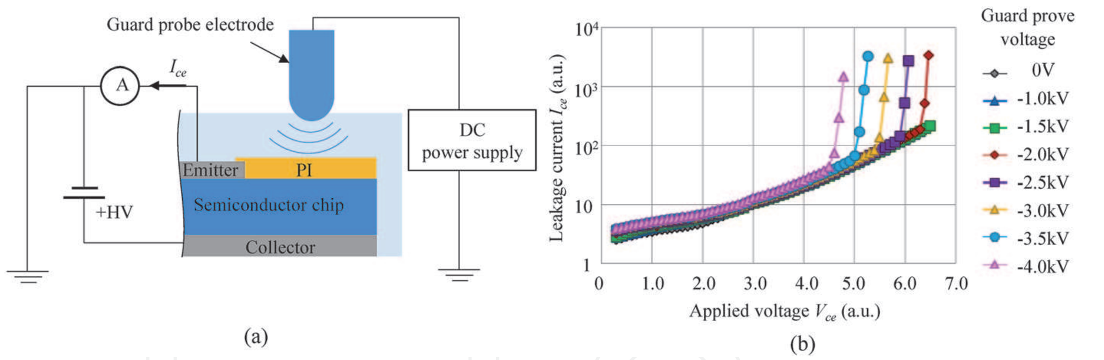

Figure 3.
(a) Schematic view of guard probe (GP) method and (b) Leakage current dependent on the guard prove voltage.

semiconductor chip. Many trials have been performed to measure the space charge characteristics in polyimide and encapsulation material such as silicone gel as described below.

Earlier reports featuring space charge in PI [10–12] reported the processes indirectly, for example, through charging current measurements or directly as with pulsed electroacoustic (PEA) method with relatively thick films (125 μm) [10]. In [10], the effect of humidity in air and the difference due to electrode material (Al and Au) on space charge formation with time evolution are discussed. Recently, the Laser Intensity Modulation Method (LIMM) [13] has been performed to investigate space charge characteristics in thin PI films with few micrometers in thickness under the DC field up to 125 kV/mm, close to breakdown voltage [14–17]. In [17], the space charge characteristics were reported under DC voltage of from low field of 2.5 to 125 kV/mm with the correlation with DC conductivity trends. Considering the encapsulation material, some studies have been performed through charge accumulation measurement in silicone gel by using PEA [18, 19] and LIPP (Laser-Induced Pressure Pulse) [20] methods, and space charge characteristics of only surface information and total amount of charge have been measured in [18–20], respectively.

As described, many attempts have been made to evaluate the influence of space charge, and quantitative evaluation has been under development, especially in thin PI. However, the space charge distribution in the PI film, which is important for providing space charge tolerance of semiconductor chip, is gradually becoming apparent along with the influence of the operating environment. In this chapter, the latest developments with space charge measurements in thin polyimide films using the LIMM method, with the focus on local field strengthening and correlation with conductivity measurements, are discussed.

2. Space charge evaluation methods

2.1 PEA method

Since the 1980s, the PEA method has been used to measure the space charge of sheet or film samples in order to investigate space charge phenomena and evaluate the aging of dielectrics. A space charge distribution by converting a pressure wave generated by applying a pulse electric field to a sample under high voltage application and converting the pressure wave into an electric signal using a piezoelectric element. The thickness of the sample that can be evaluated by PEA is more than 100 μm, and its spatial resolution is about several tens of micrometers.

2.2 (F)LIMM method

The (Focused) Laser Intensity Modulation Method or (F)LIMM is a thermal wave method dedicated to the space charge analysis of thin dielectric films (with a thickness from 5 to 50 μm) [21, 22]. This method is originally proposed by Lang [23] in the 1980s, and the characterization of space charge distribution had been performed under volt-off after external DC voltage application. Recent development has been reported that LIMM measurement is carried out under volt-on [24]. The LIMM is much suitable to clarify the space charge characteristics in a polymer film with only several micrometer thickness, which is a typical thickness of passivation layer on a semiconductor chip. **Figure 4** shows the schematic diagram of online LIMM. A DC potential (V_{ht}) is applied to the top electrode of the measuring cell through a low-pass filter. (F)LIMM currents are recorded after pre-amplification and extracted from noise by a lock-in amplifier. To protect a damage from an eventual breakdown of the sample, an electrical protection device was introduced at the output of the measuring cell.

The thermal gradient created by the laser beam induces periodical and local expansions that lead to relative charge displacement regarding to the electrodes within the irradiated volume. Varying the laser beam modulation frequency, one can control the depth of thermal diffusion and then calculate its effect on the total current signal. Finally, a mathematical treatment allows charge density profile reconstruction in the direction of the sample thickness. A modulated laser beam of a frequency f heating a surface S of a top electrode sputtered on a dielectric nonpolar sample of thickness L, to which an additional DC voltage V_{ht} is applied, the fundamental (F)LIMM equation for the complex current $I(f)$ can be expressed by [24]:

$$I(f) = -j\frac{2\pi f}{L}(\alpha_z - \alpha_\varepsilon)\varepsilon S\left[\int_0^L E_i(z)T(z,f)dz + \frac{V_{ht}}{L}\int_0^L T(z,f)dz\right] \tag{1}$$

where z is the direction normal to the sample, α_z is the coefficient of thermal expansion (K^{-1}), αε is the coefficient of thermal dependence of the dielectric permittivity (K^{-1}), ε is the permittivity, $E_i(z)$ is the internal electric field along z-axis ($V.m^{-1}$), and $T(z,f)$ is the simulated spatial variation of the temperature versus frequency.

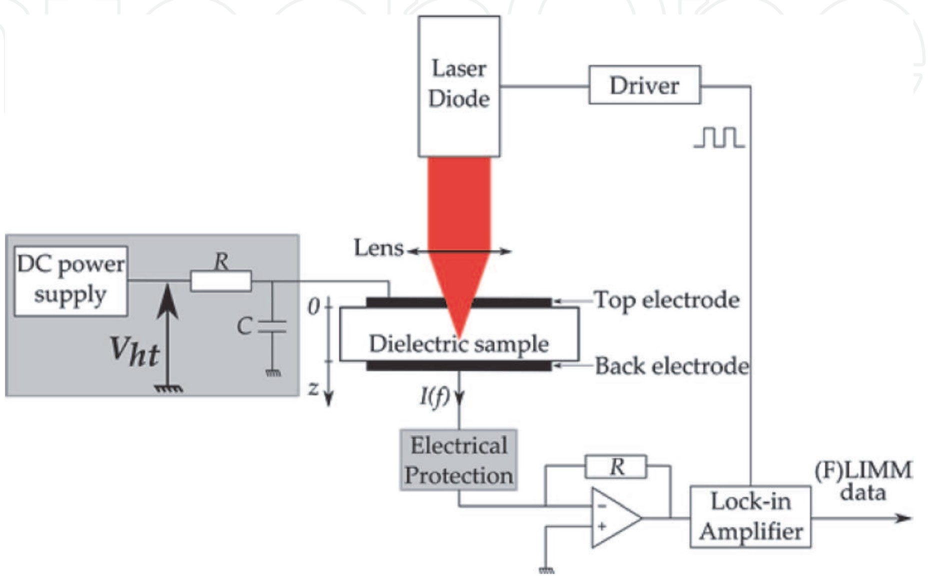

Figure 4.
Schematic diagram of (F)LIMM [24].

3. Space charge behavior in polyimide film

3.1 Space charge distribution in polyimide film

In this subsection, the LIMM measurement results of PI film in a typical case using cumulative DC voltage application. **Figure 5** shows the sample structure and the example of LIMM measurement protocol. The thickness of PI film is 20 μm. The polarization steps consist in applying a DC electric field from 25 to 125 kV/mm with positive or negative polarity. The corresponding positive or negative DC voltages are applied on the top electrode of the sample in air at room temperature, whereas the Si substrate is grounded. After each polarization step, a depolarization process is performed by short-circuiting the sample. A cumulative protocol is applied for successive voltage steps on the sample as shown in the right side of **Figure 5**. Volt-on and volt-off steps of each 60 min are applied on the sample from 25 to 125 kV/mm, with the steps of 25 kV/mm. LIMM measurements are performed throughout the whole protocol, with every 10 min scanning of 63 frequency points from 10 Hz to 10 kHz.

Figure 6 shows LIMM current waveform under the field of 25, 50, 75, 100, and 125 kV/mm, positive polarity. The space charge and internal electric field

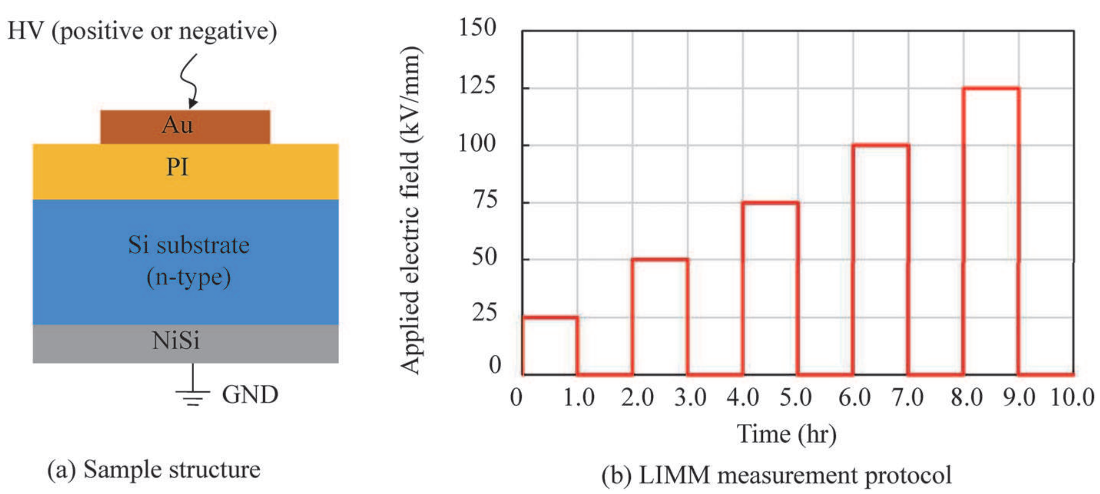

Figure 5.
Typical sample structure and LIMM measurement protocol (cumulative voltage application of 25–125 kV/mm, positive polarity).

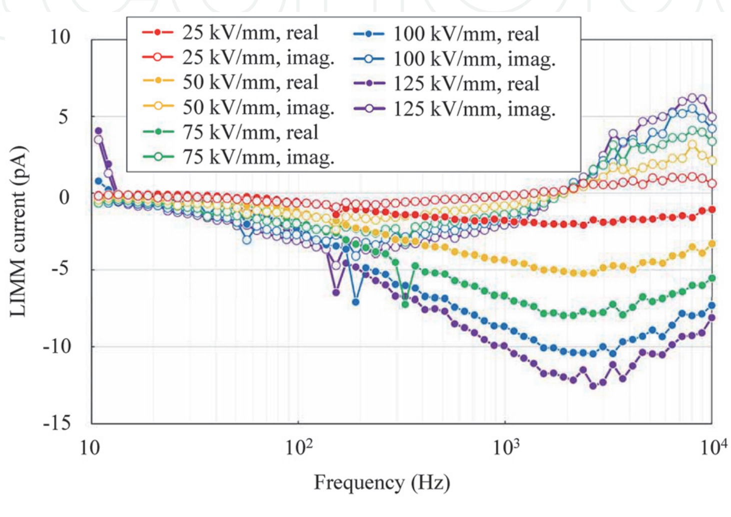

Figure 6.
Example of LIMM current waveform (25–125 kV/mm, positive polarity).

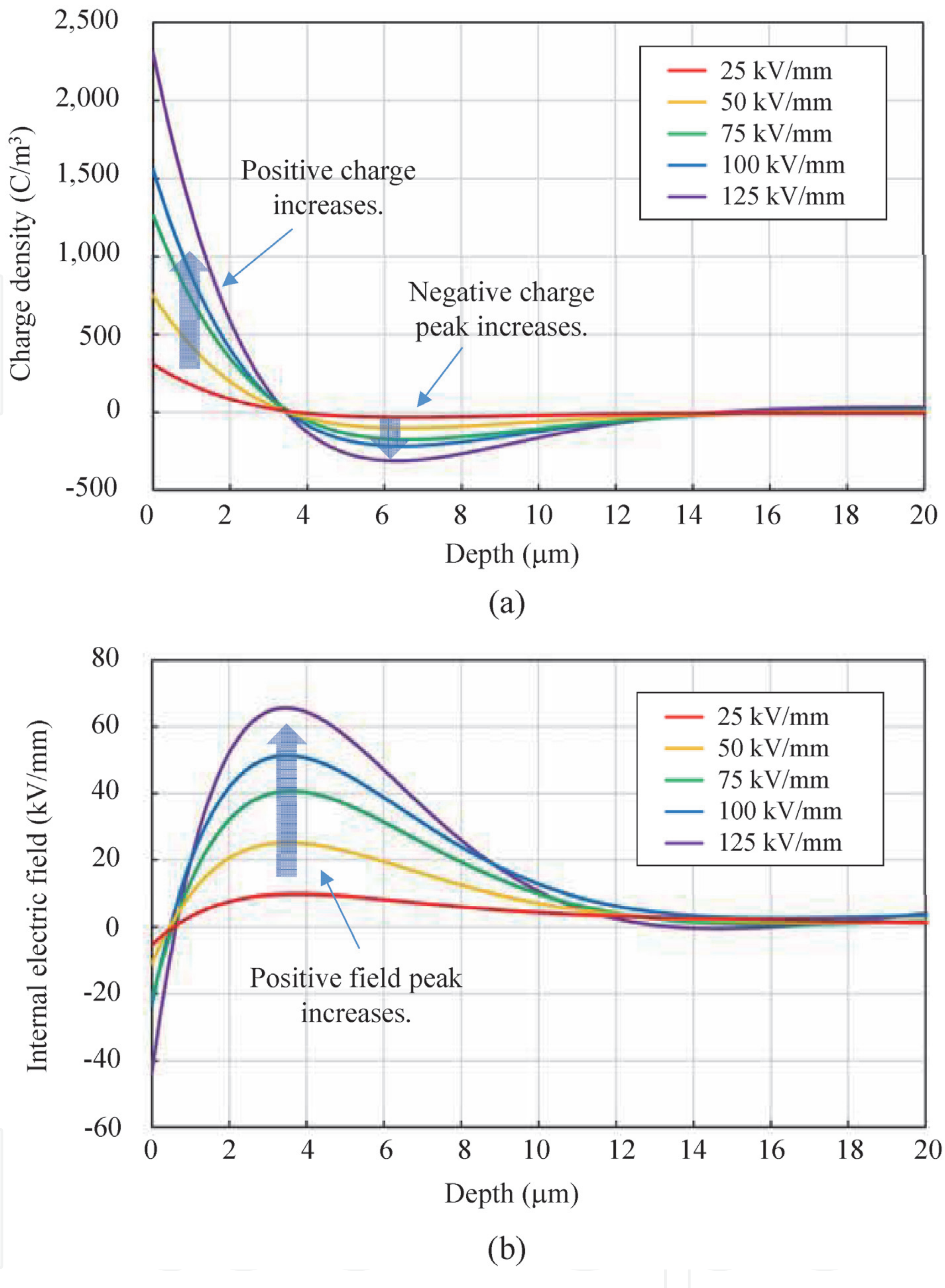

Figure 7.
Example of the depth profiles of (a) space charge and (b) internal electric field (25–125 kV/mm, positive polarity).

distributions are deduced from Eq. (1) as shown in **Figure 7(a)** and **(b)**, respectively. In this case, positive and negative space charges are confirmed close to and at the depth of from 4 to 10 μm from top Au electrode, respectively, which causes the enhancement of positive field strengthening at 2–6 μm depth. The maximum values of these are confirmed to increase along with the applied DC field. Time evolution of maximum peaks of enhanced electric field in both polarities is shown in **Figure 8**. As mentioned so far in this subsection, the space charge and enhanced electric field characteristics in polyimide under external DC voltage on and off can be evaluated by using LIMM method including both depth-profile and time evolution.

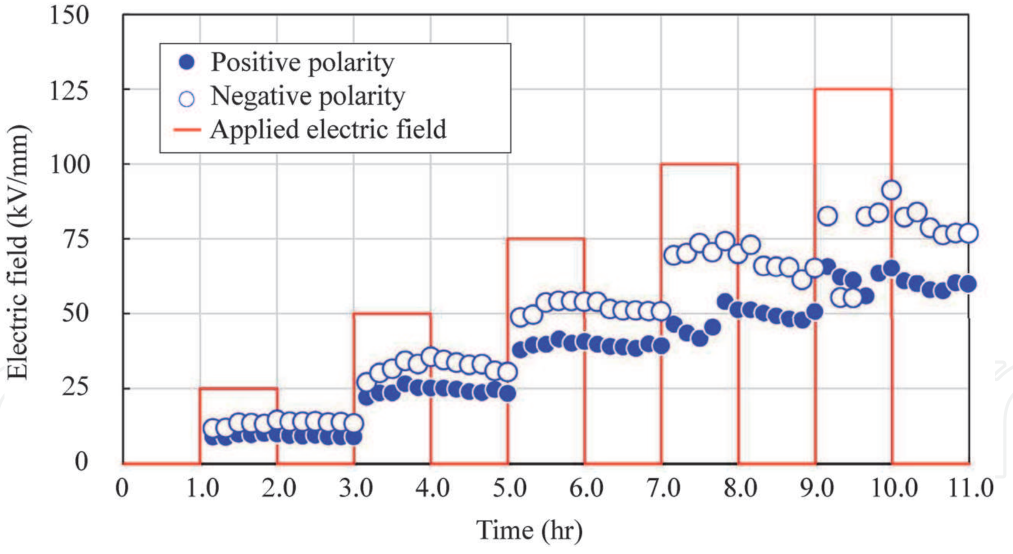

Figure 8.
Magnitude of positive peaks of internal electric field.

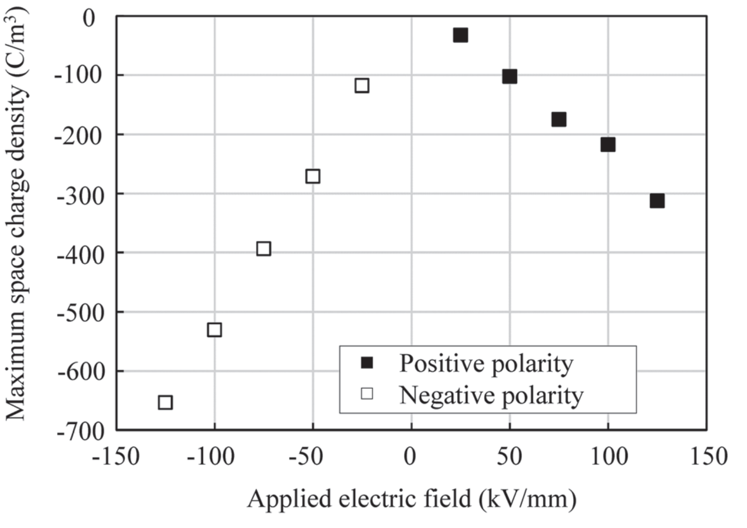

Figure 9.
Maximum negative space charge density.

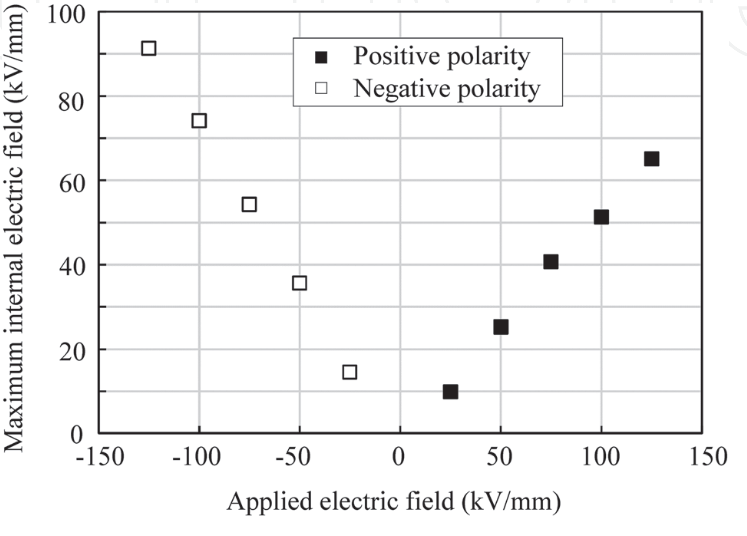

Figure 10.
Maximum positive internal electric field.

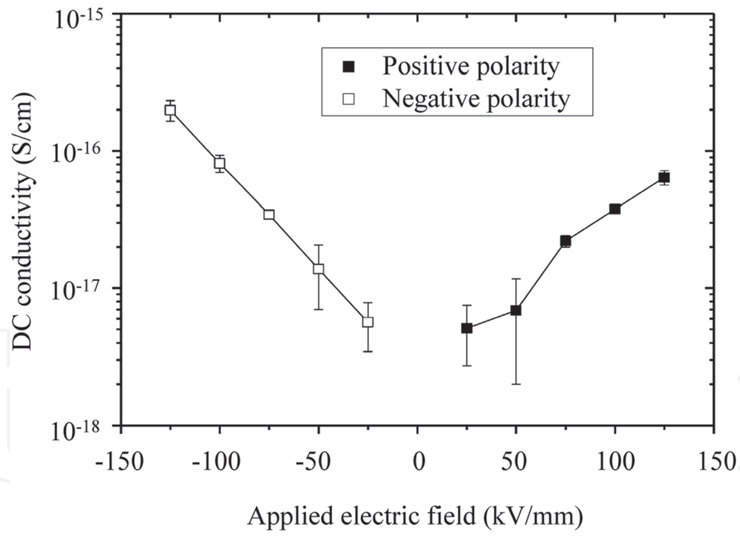

Figure 11.
DC conductivity.

3.2 DC conductivity

To clarify the influence of space charge accumulation to the conductivity behavior, space charge density and internal electric field are compared with DC conductivity. **Figures 9–11** show the maximum space charge density of negative charge, maximum positive internal electric field, and DC conductivity, respectively, under the applied field from 25 to 125 kV/mm for both polarities. To compare these figures, no remarkable influence on the conductivity by space charge accumulation inside polyimide at this level works. To establish a direct link between space charge dynamics and conduction phenomena, further evaluations are still necessary.

4. Effect of space charge on semiconductor devices

As described in Section 1, the degradation (increase) of leakage current of the device is caused possibly by the formation of space charge on the surface at

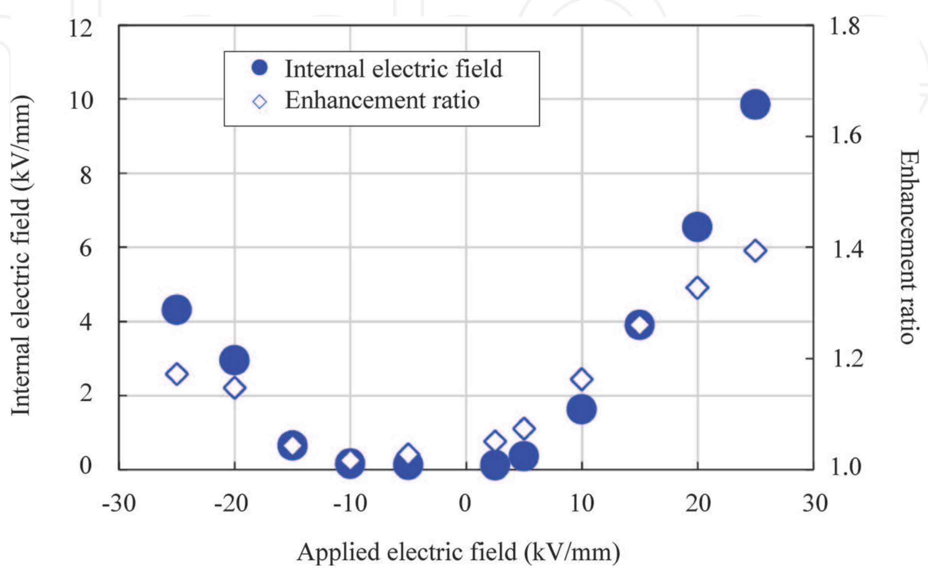

Figure 12.
Peak value of internal electric field linked to field strengthening (filled circle) and enhancement ratio of those peaks (open square) versus applied electric field.

semiconductor edge termination area. **Figure 12** shows that the electric field enhancement ratio defined in Eq. (2) confirmed in the LIMM measurement depending on the applied DC field of from −25 to 25 kV/mm. It is confirmed that the enhancement ratio in PI film is negligibly small (less than 1.1) for applied fields less than 10 kV/mm. However, it can reach much higher like 1.4 at higher applied field like 25 kV/mm.

$$Enhancement\ ratio = \frac{Applied\ electric\ field + Measured\ electric\ field}{Applied\ electric\ field} \tag{2}$$

This result implies that electric field at edge termination area should be carefully designed under such an operational electric field as is the case of SiC devices to prevent the influence of space charge accumulation. It should be noted that not only inside polyimide, but also space charge accumulations in encapsulation material and the interface between polyimide and encapsulation as its structure shown in **Figure 1** are also needed to be clarified. Moreover, the influence of environmental conditions such as temperature and humidity on the space charge behavior should be taken into account.

5. Conclusion

It has been presented that the space charge distribution can be clarified in thin polyimide film using LIMM method from relatively low field of 2.5 kV/mm up to 125 kV/mm, which is close to breakdown field. The electric field enhancement due to space charge accumulation is shown to be 1.4 times at 25 kV/mm under room temperature condition. To design much reliable structure against space charge accumulation in polyimide and encapsulation material, its distributions are needed to be clarified by the further study.

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