Fast Measurement of Dielectric Conductivity for Space Application by Surface Potential Decay Method *

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Surface potential decay of polymers for electrical insulation can help to determine the dark conductivity for spacecraft charging analysis. Due to the existence of radiation-induced conductivity, it decays fast in the first few hours after irradiation and exponentially slowly for the remaining time. The measurement of dark conductivity with this method usually takes the slow part and needs a couple of days. Integrating the Fowler formula into the deep dielectric charging equations, we obtain a new expression for the fast decay part. The experimental data of different materials, dose rates and temperatures are fitted by the new expression. Both the dark conductivity and the radiation-induced conductivity are derived and compared with other methods. The result shows a good estimation of dark conductivity and radiation-induced conductivity in high-resistivity polymers, which enables a fast measurement of dielectric conductivity within about 600 min after irradiation.

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Space energetic electrons can penetrate into satellites and result in serious deep dielectric charging problems.[1–3] Dark conductivity and radiation-induced conductivity are key parameters to determine whether the dielectric could be charged up to high risk level.[4,5] The industrial standard test method for electrical conductivity is not suitable for space application, as their charge injection mechanism and electrode setting are quite different. A common method proposed by Frederickson and Dennison is to measure the surface potential decay on dielectrics after electron irradiation and then its dark conductivity can be obtained by fitting the expression with experimental data[6]

$$V(t) = V(0)e^{-\frac{\sigma_{\rm dark}}{\varepsilon_0\varepsilon_{\rm r}}t}, \tag{1}$$

where $\sigma_{\rm dark}$ is the dark conductivity, $V(t)$ is the surface potential variation with time, and $V(0)$ is the initial surface potential. As the radiation-induced conductivity is not included in the expression, the measuring data in the first few hours after irradiation is usually ignored, which contributes most of the decay part especially on high-resistivity polymers. As a result the measurements usually take several days. To shorten the measuring time, we propose a new expression including the radiation-induced conductivity effect, which fits the fast decay part of surface potential just after irradiation.

For a grounded dielectric slab, the potential decay on its surface after electron irradiation follows the deep dielectric charging equations[7,8]

$$V(t) = \int_0^d E(x,t)dx, \tag{2}$$

$$E(x,t) = \int_0^x \frac{\rho(\xi,t)}{\varepsilon_0\varepsilon_{\rm r}}d\xi, \tag{3}$$

$$\frac{\partial\rho(x,t)}{\partial t} + \nabla J(x,t) = 0, \tag{4}$$

$$J(x,t) = (\sigma_{\rm dark} + \sigma_{\rm ric})E(x,t), \tag{5}$$

where $V(t)$ is the dielectric surface potential, $E(x,t)$ is the electric field inside the dielectric, d is the thickness of sample, $\rho(x,t)$ is the free charge density, $J(x,t)$ is the current density, $\sigma_{\rm dark}$ is the dark conductivity, and $\sigma_{\rm ric}$ is the radiation-induced conductivity. When the electron beam is cut off, the radiation-induced conductivity decreases with time, following the Fowler formula[9]

$$\sigma_{\rm ric}(t) = \frac{\sigma_{\rm ric}(0)}{1+bt}, \tag{6}$$

where $\sigma_{\rm ric}(0)$ is the initial RIC at the time stopping irradiation, and b is a constant.[8] By solving Eqs. (3)–(6), the charge density $\rho(x,t)$ can be obtained

$$\rho(x,t) = \rho(x,t_0)e^{-\frac{\sigma_{\rm dark}}{\varepsilon_0\varepsilon_{\rm r}}}(1+bt)^{-\frac{\sigma_{\rm ric}(0)}{b\varepsilon_0\varepsilon_{\rm r}}}. \tag{7}$$

Thus with Eq. (2), the new expression for surface po-

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tential decay after radiation is

$$V(t) = \int_0^d \int_0^x \frac{\rho(\xi,t)}{\varepsilon_0\varepsilon_r} d\xi dx$$
$$= \int_0^d \int_0^x \frac{\rho(\xi,t_0)}{\varepsilon_0\varepsilon_r} \frac{e^{-\frac{\sigma_{dark}}{\varepsilon_0\varepsilon_r}t}}{(1+bt)^{\frac{\sigma_{ric}(0)}{b\varepsilon_0\varepsilon_r}}} d\xi dx$$
$$= V(0)\frac{e^{-\frac{\sigma_{dark}}{\varepsilon_0\varepsilon_r}t}}{(1+bt)^{\frac{\sigma_{ric}(0)}{b\varepsilon_0\varepsilon_r}}}. \quad (8)$$

As we can see, Eq. (8) describes the surface potential variation after irradiation correlating with both dark conductivity and radiation-induced conductivity. When the radiation-induced conductivity is negligible, Eq. (8) becomes Eq. (1) by using the common method.

To examine the new expression, experiments are carried out in a vacuum chamber with FR4, polyimide and teflon samples of 2 mm thickness. Irradiation is performed by electron beam from Sr^{90} radioactive source. When the sample is charging up to −3000 V, the electron beam is cut off and its surface potential is recorded for the following about 35 h with precision better than 5%. After that, the experimental data of the first 10 h is fitted by Eq. (8), compared with the last 10 h fitted by Eq. (1).

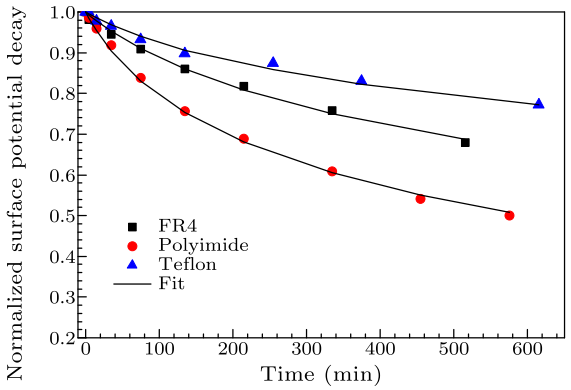


Fig. 1. Normalized surface potential decay of FR4, polyimide and teflon after irradiation. The solid scatters present the experimental data, and the solid lines are the fitting curves with Eq. (8).

Figure 1 shows the normalized surface potential decay of FR4, polyimide, teflon and their fitting curves with Eq. (8). Sample temperature is 20℃ and dose rate is 6.8 Gy/s. The dark conductivity derived by Eq. (8) is 7.14×10^{-17} S/m for FR4, 1.42×10^{-16} S/m for polyimide and 1.98×10^{-17} S/m for teflon. The result by Eq. (1) is 1.81×10^{-16} S/m for FR4, 1.80×10^{-16} S/m for polyimide and 5.52×10^{-17} S/m for teflon. When the sample is measured by an Agilent 4339B with the industrial standard method, the FR4 dark conductivity becomes 2.05×10^{-14} S/m, polyimide is 2.20×10^{-14} S/m and teflon is 3.11×10^{-15} S/m. We can see that Eq. (8) gives the lowest dielectric dark conductivity, but still is in the same order with the results from Eq. (1). They both are two orders below the results from the industrial standard method, but consistent with NASA-HDBK-4002A.[10] Meanwhile, with Eq. (8), the initial radiation-induced conductivity can also be calculated, which is 8.5×10^{-16} S/m for FR4, 1.85×10^{-15} S/m for polyimide and 3.01×10^{-16} S/m for teflon. The initial radiation-induced conductivity is about one order above its dark conductivity. The constant b varies from $1\times10^{-4}\,s^{-1}$ to $2\times10^{-4}\,s^{-1}$.[11] That is the reason for the fast decay of surface potential in the first few hours after irradiation.

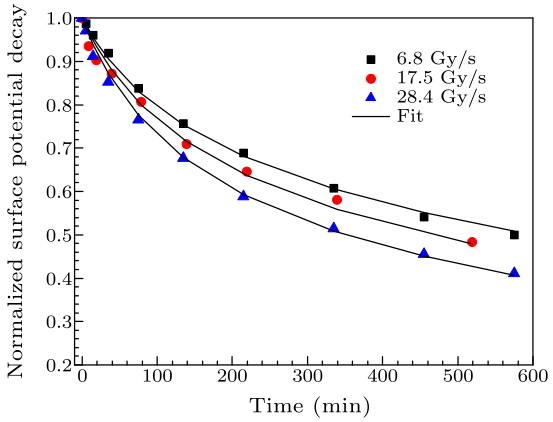


Fig. 2. Normalized surface potential decay of polyimide after irradiation with different dose rates. The solid scatters present the experimental data, and the solid lines are the fitting curves with the new expression. The experimental temperature is 20℃.

To further verify the new expression, the surface potential decay is measured on polyimide at different dose rates in Fig. 2. Due to the effect of the remaining radiation-induced conductivity, the higher dose rate leads to faster decay while the dark conductivity remains the same. Equation (8) gives the dark conductivity of polyimide between 1.40×10^{-16} S/m–1.42×10^{-16} S/m and the initial radiation-induced conductivities are 1.85×10^{-15} S/m under 6.8Gy/s, 2.12×10^{-15} S/m under 17.5 Gy/s, and 2.62×10^{-15} S/m under 28.4 Gy/s. It grows with dose rate but does not completely fulfill the power law due to the thickness of polyimide samples.[12] When most electrons cannot pass through the sample but deposit in the sample, the effect of radiation-induced conductivity on surface potential is weakened by the movement of free charges inside the sample.[13] However, the result in Fig. 2 still shows that we can obtain a good estimation of dielectric dark conductivity at different dose rates with Eq. (8).

Figure 3 shows the influence of temperature on surface potential decay rate. In Fig. 3, the surface potential decays fastest at 60℃, and slowest at 20℃. Equa-

tion (8) gives the sample's dark conductivity as 2.5×10^{-15} S/m, 1.42×10^{-16} S/m and 3.55×10^{-19} S/m for temperatures −20℃, 20℃ and 60℃, with the initial radiation-induced conductivity as 1.71×10^{-15} S/m, 1.85×10^{-15} S/m and 1.07×10^{-14} S/m. Under the same dose rate, the radiation-induced conductivity usually grows with temperature.[14,15] An interesting phenomenon is that the sample's dark conductivity decreases with temperature, which results in the slowest decay at 20℃ in Fig. 3. On the other hand, with Eq. (1) we can only obtain the dark conductivity at temperatures −20℃ (7.28×10^{-16} S/m) and 20℃ (1.8×10^{-16} S/m). As the surface potential decreases so fast at temperature 60℃, it loses 80% of its surface potential within 200 min. As a result, there is not enough time to wait for the measurement by Eq. (1).

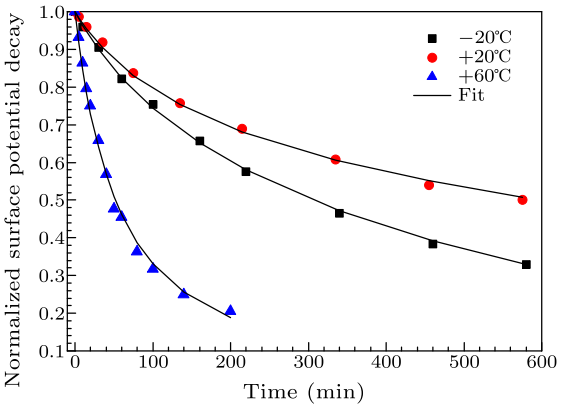


Fig. 3. Normalized surface potential decay of polyimide at different temperatures. The solid scatters present the experimental data, and the solid lines are the fitting curves with the new expression. The dose rate before measurement is 6.8 Gy/s.

In summary, by fitting the surface potential decay data of high-resistivity dielectrics to a new expression, we suggest that the dark conductivity can be derived from the first 10 h data, indicating a fast measurement of dielectric conductivity for space application. Moreover, the initial radiation-induced conductivity can also be derived by the new expression, which provides a method to estimate the radiation-induced conductivity after irradiation.

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