The Influence of Space Radiation on the Relative Permittivity of Dielectrics

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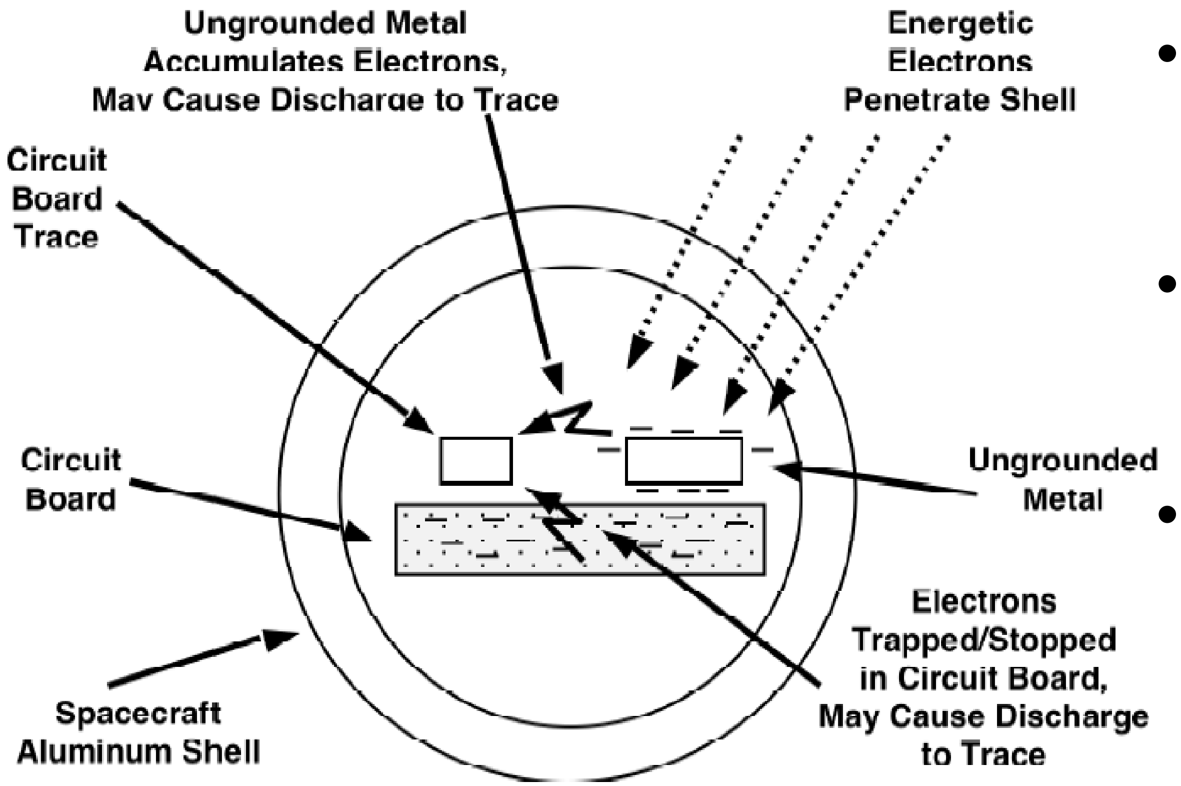
Introduction

Introduction

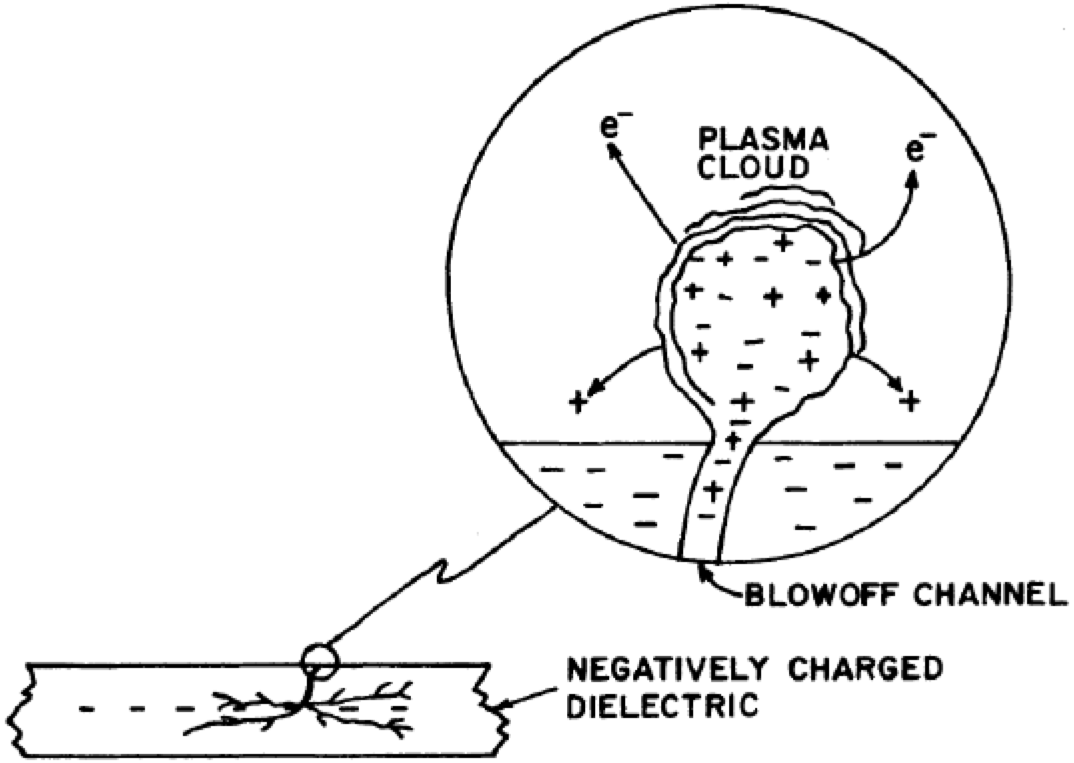


[NASA-HDBK-4002A]

- Energetic electrons will penetrate into interior portions of a spacecraft.
- Electrons may be stopped in dielectrics or on ungrounded conductors.
- If too many electrons accumulate, the resultant high electric fields may cause an ESD to a nearby victim circuit.

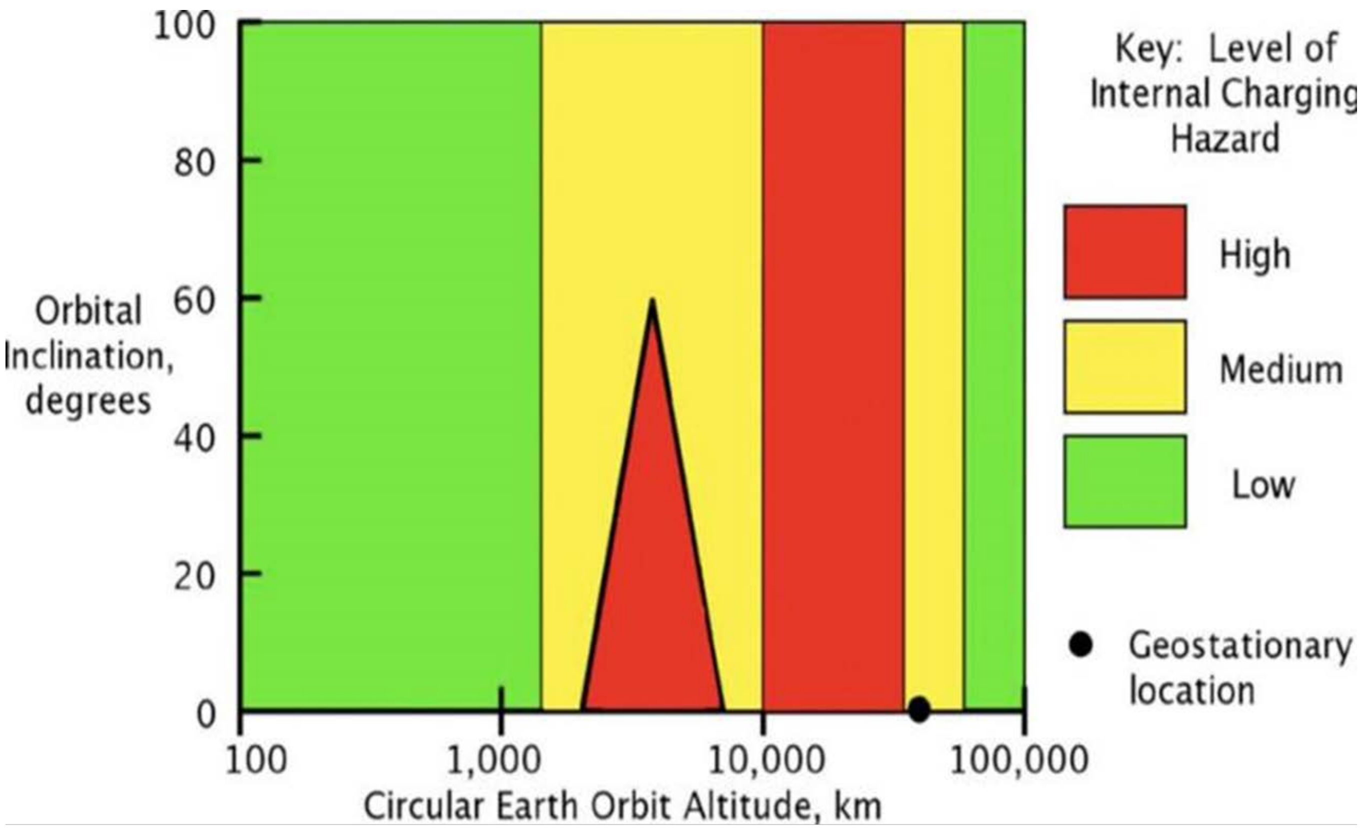
Introduction

- Discharge creates a local plasma.
- Current increases on nearby conductors that are grounded.
- Voltage of the dielectrics decreases.
- Discharge pulses can be detected.



[A.R.Frederickson,1983]

Introduction

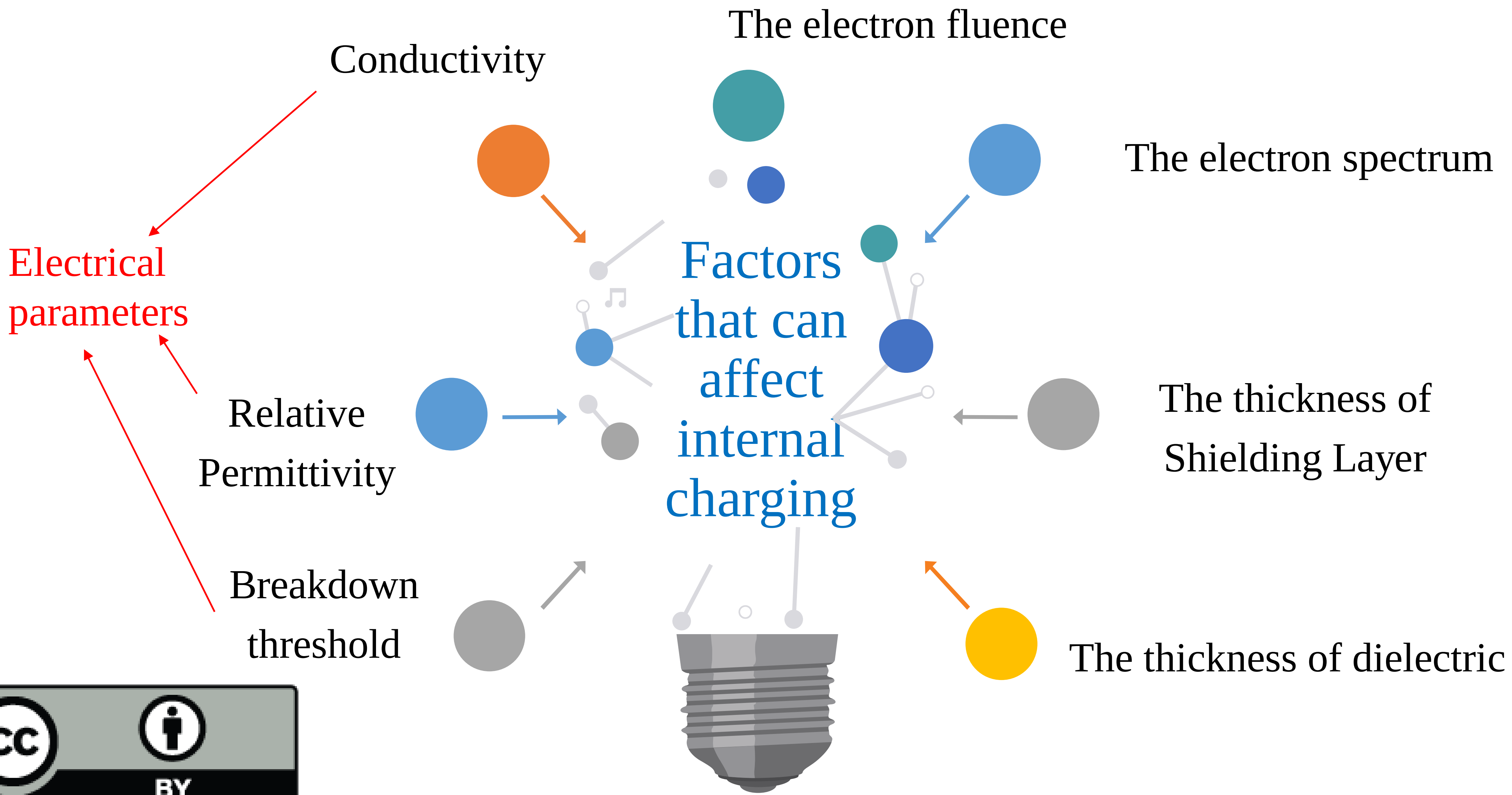


[NASA-HDBK-4002A]

- Earth's internal charging threat regions is estimated assuming averages electron fluence over several orbits.

- Satellites on MEO and GEO orbits are at high risk of internal charging threat.

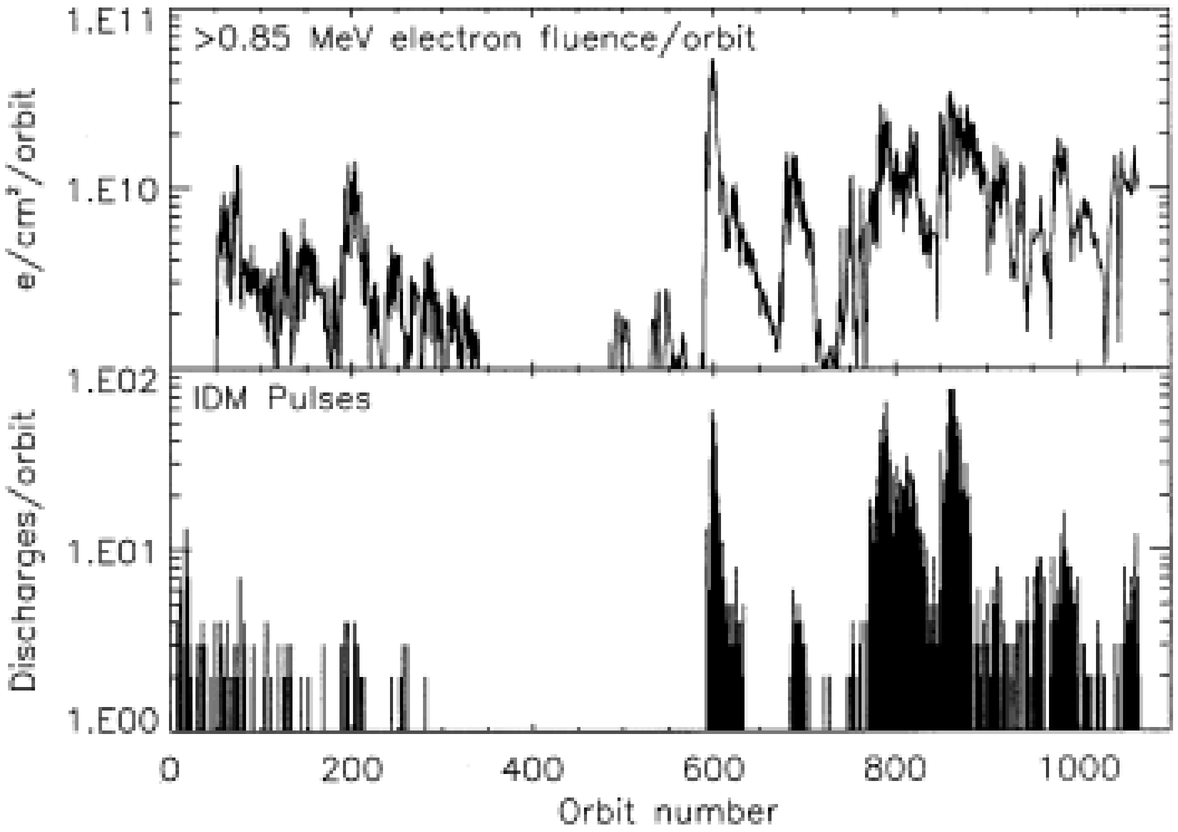
Introduction



Phenomena

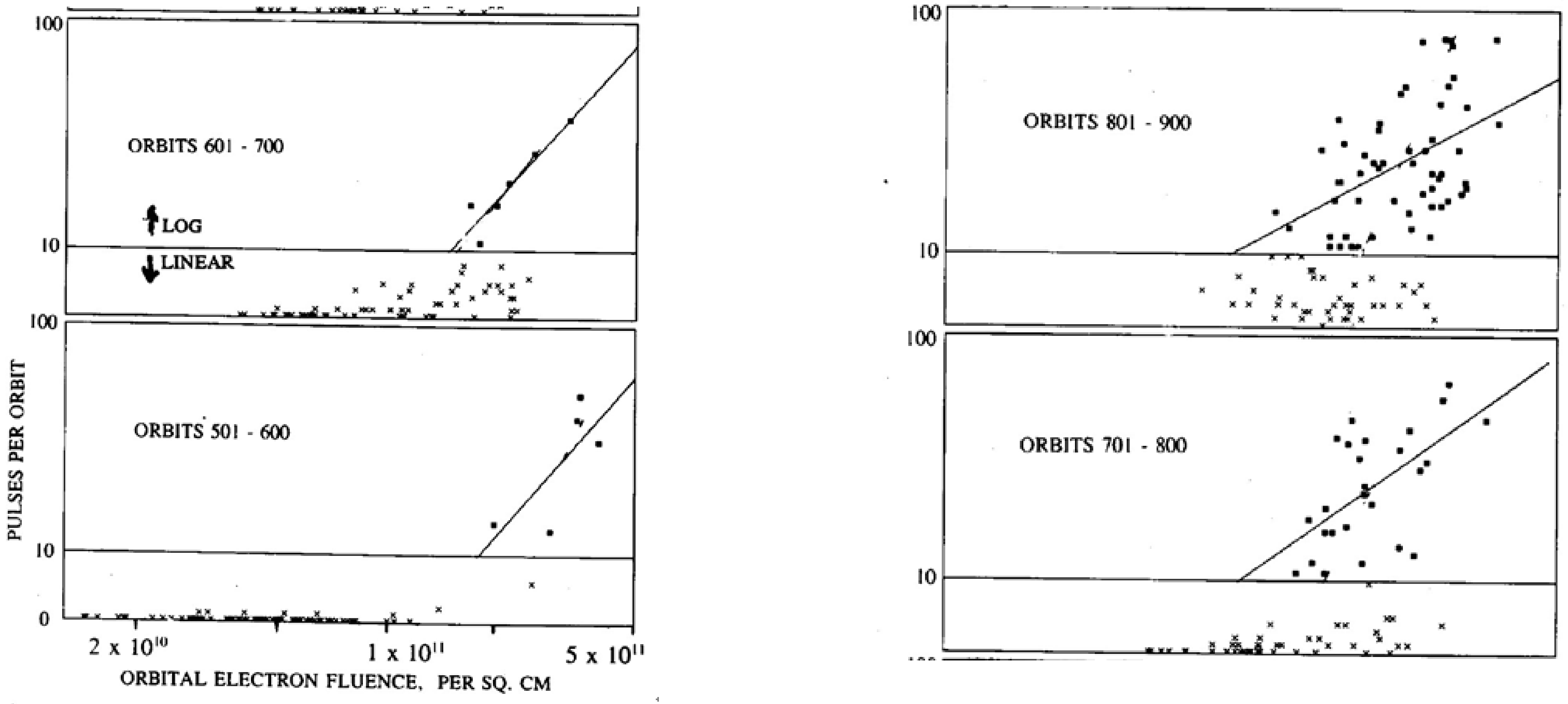
- CRRES was launched on 1990, carrying a electron detector, Internal Discharge Monitor(IDM), 16 different dielectric samples.

- The electron fluence and discharge pulses of each sample per orbit is collected.



[A.R.Frederickson, 1992]

Phenomena

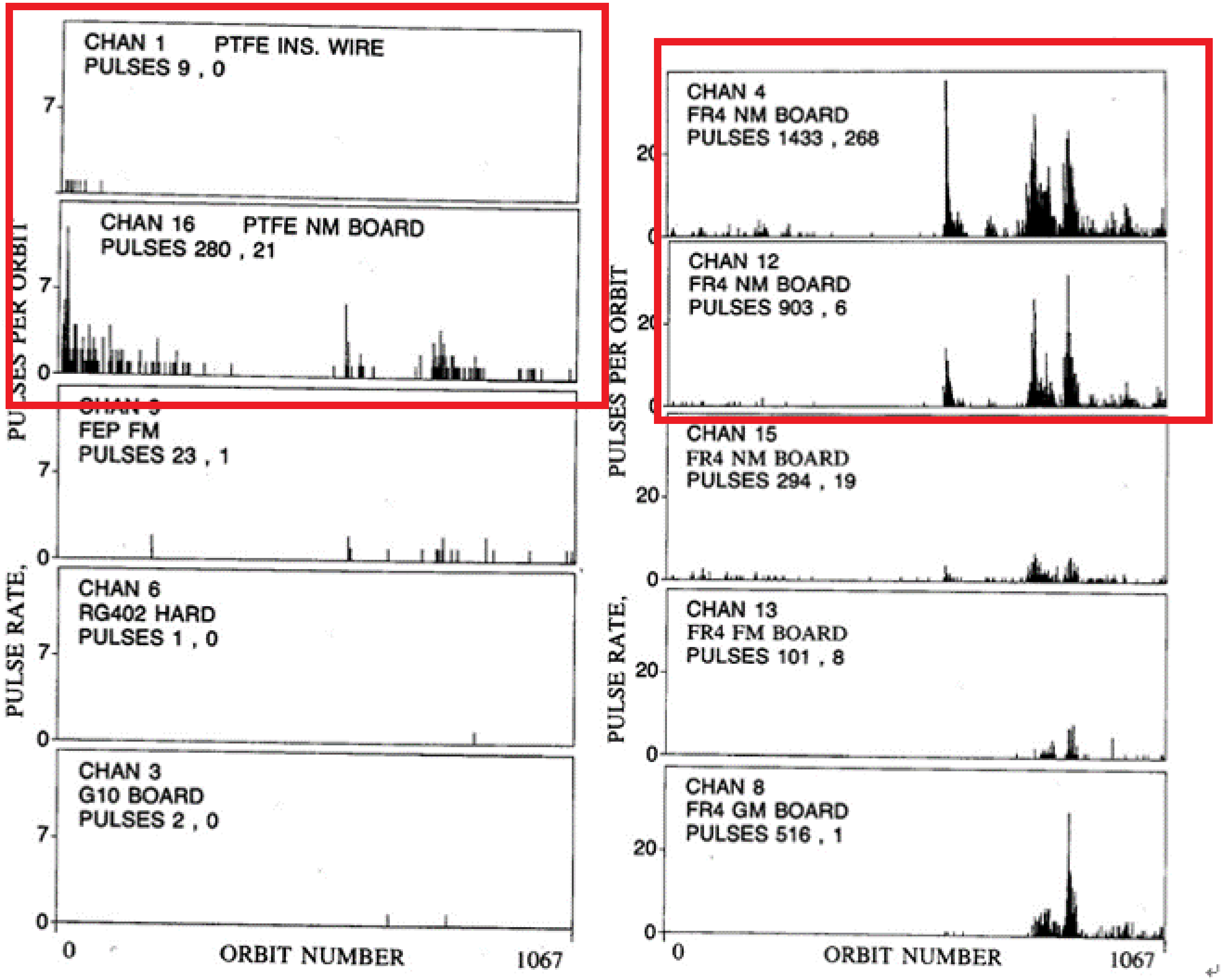


[A.R.Frederickson, 1992]

- No clear relationship between pulses and orbital electron fluence.

Phenomena

- The discharge frequency of different samples changed with the increase of time.
- The accumulated electron radiation dose may affect properties of the dielectric samples.

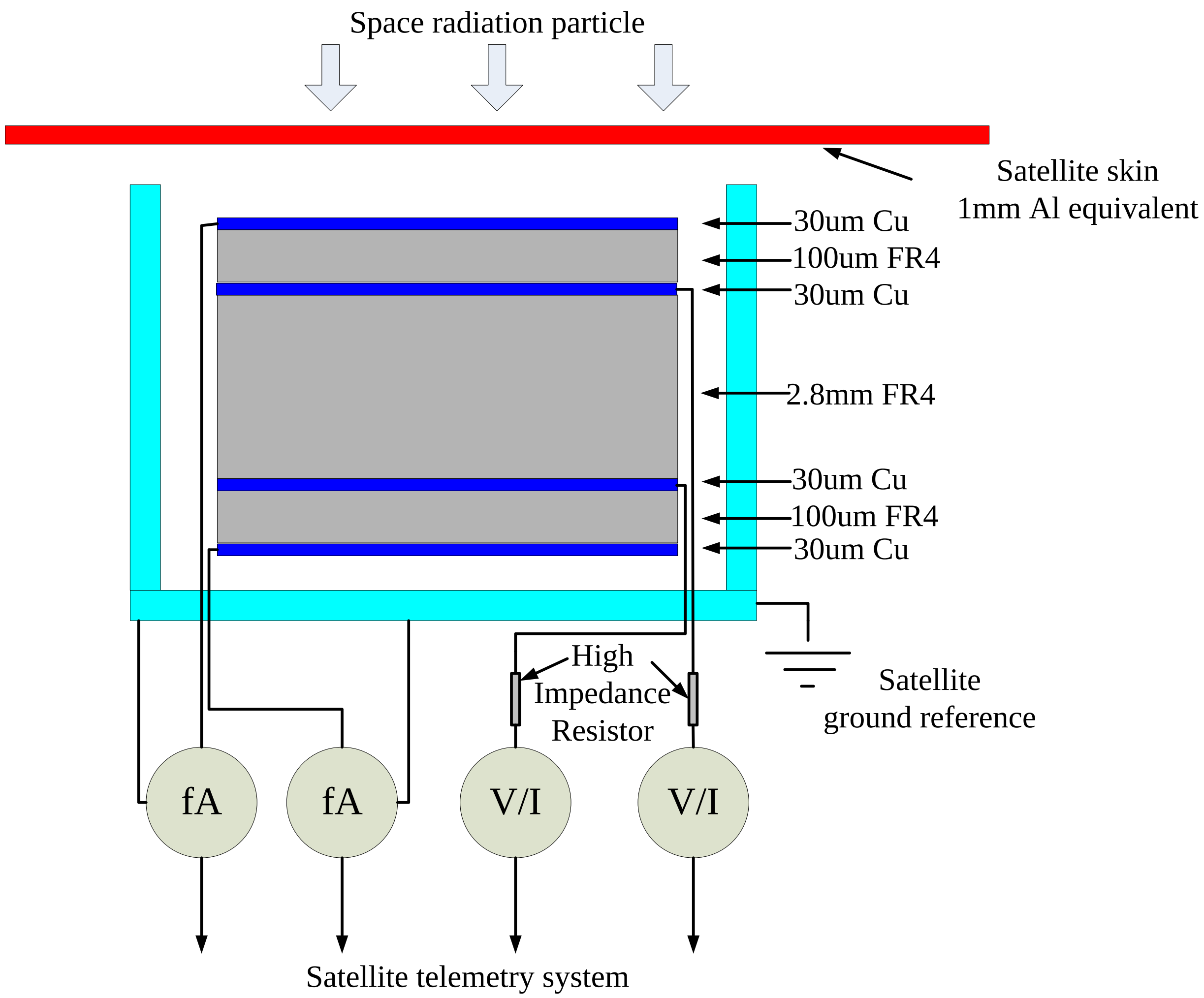


[A.R.Frederickson, 1992]

Phenomena

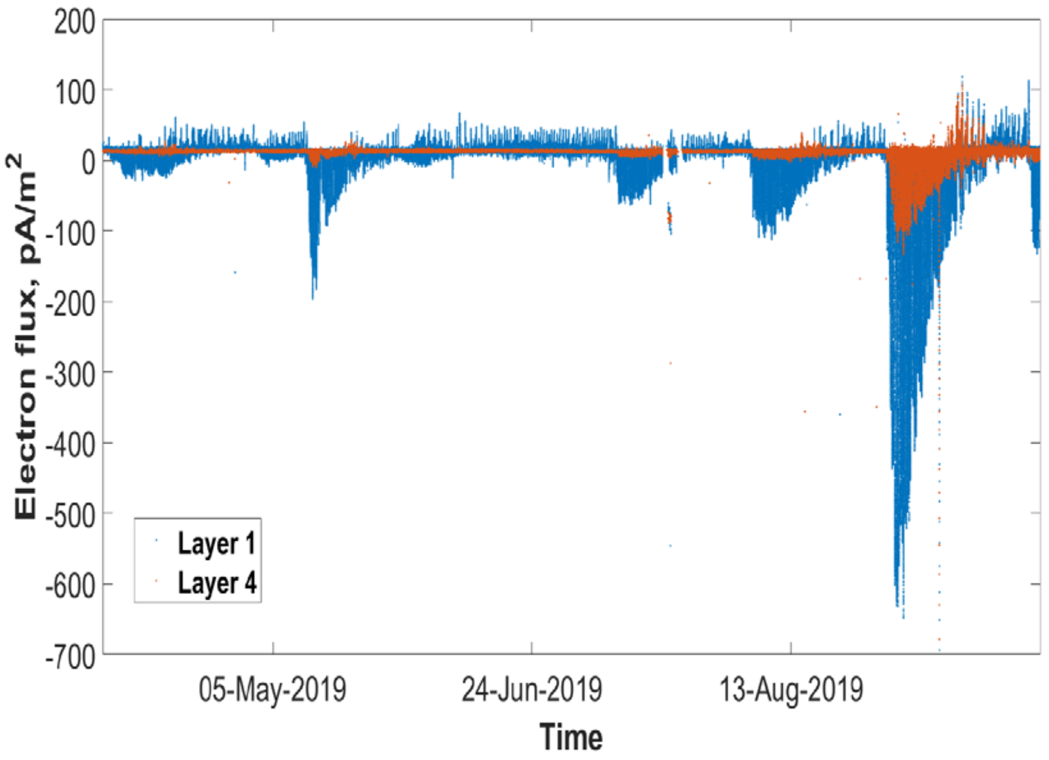
- The Deep Dielectric Charging Effects Monitor(DDCEM) carried by BD3M17 satellite was launched on Nov 1st, 2018.

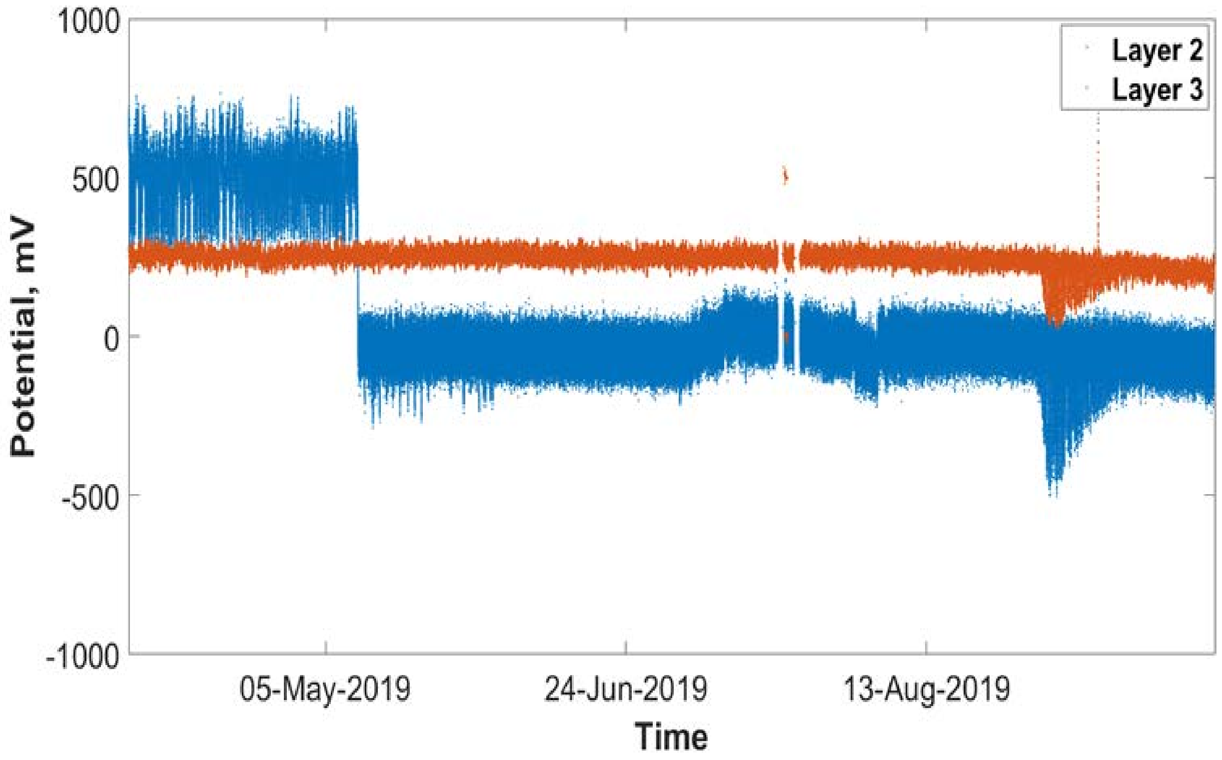
- DDCEM can monitor leakage current and internal potential of FR4 samples.



[Yu Xiangqian, 2019]

Phenomena





[Yu Xiangqian, 2019]

- Internal potential decreased with the increase of time.
- Dielectric properties may have changed due to the electron radiation dose.

Geant4-RIC

Poisson Equations

$$\varepsilon\frac{\partial E(x,t)}{\partial x} = \rho_-(x,t) + \rho_{t-}(x,t),$$

The equation of continuity

$$\mu_-\rho_-(x,t)E(x,t) + \sigma(x)E(x,t) + J(x) + \varepsilon\frac{\partial E(x,t)}{\partial t} = J_0(x,t),$$

The rate equation for deep trapping of negative charges

$$\frac{\partial \rho_{t-}(x,t)}{\partial t} = \frac{\rho_-(x,t)}{\tau_-}\left(1 - \frac{\rho_{t-}(x,t)}{\rho_m}\right),$$

The equation of voltage

$$V(x,t) = -\int_0^x E(x,t)\,\mathrm{d}x.$$

$$\sigma = \sigma_d + \sigma_r = \sigma_d + k\dot{D}^{\Delta}.$$

The equation of conductivity containing RIC and E

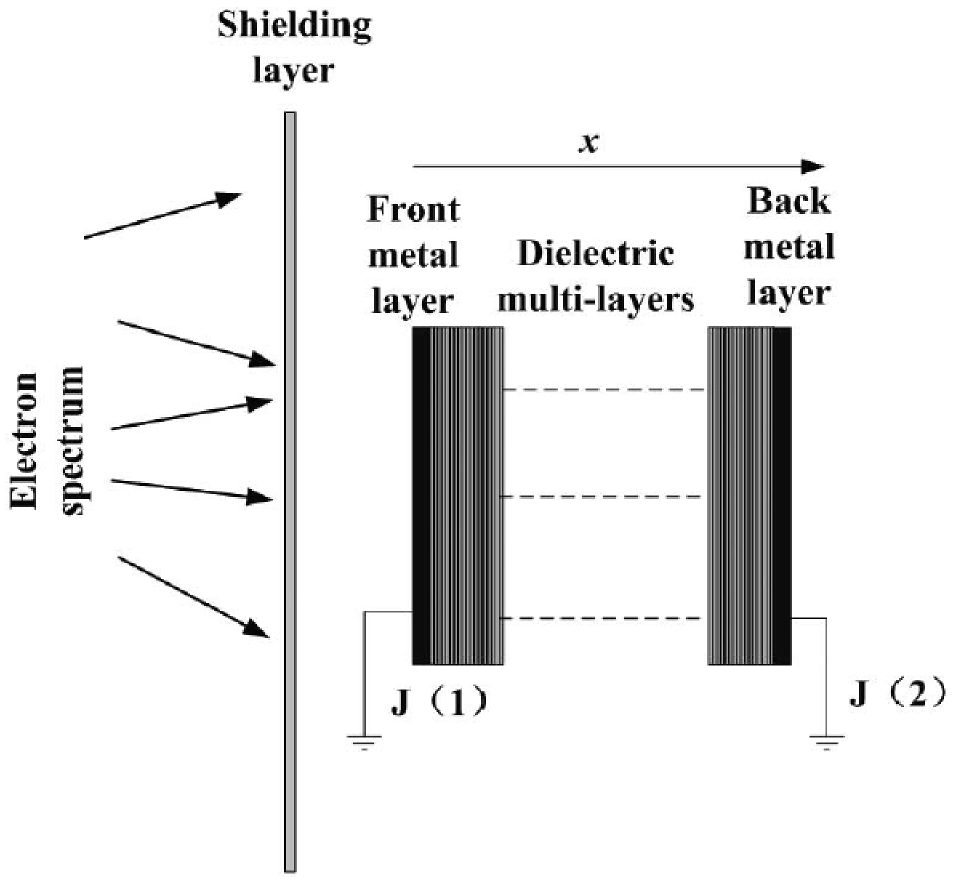
$$\frac{\sigma}{\sigma_0} = \frac{2 + \cosh\left(\beta_F E^{1/2} / 2k_B T\right)}{3},$$

Geant4-RIC

$$\dot{D} = 1.6\times10^{-11}\cdot\frac{E_d}{T_s\rho A_m\Delta x},$$

$$J = -\frac{Qe}{T_s A_m},$$

- The radiation dose rate and current density are calculated by the Monte Carlo method of Geant4



[Yu Xiangqian, 2016]

Geant4-RIC

- If E(x,0)=0, V(x,0)=0 j is constant

The electric field of dielectric during the charge process is:

$$\mathrm{E} = \frac{\mathrm{j}}{\sigma}\left[1 - \exp\left(-\frac{\sigma t}{\varepsilon}\right)\right]$$

The electric field of dielectric during the discharge process is:

$$\mathrm{E} = E_0 \exp\left(-\frac{\sigma t}{\varepsilon}\right)$$

The time constant of charge and discharge is：

$$\tau = \frac{\varepsilon}{\sigma}$$

1 Introduction

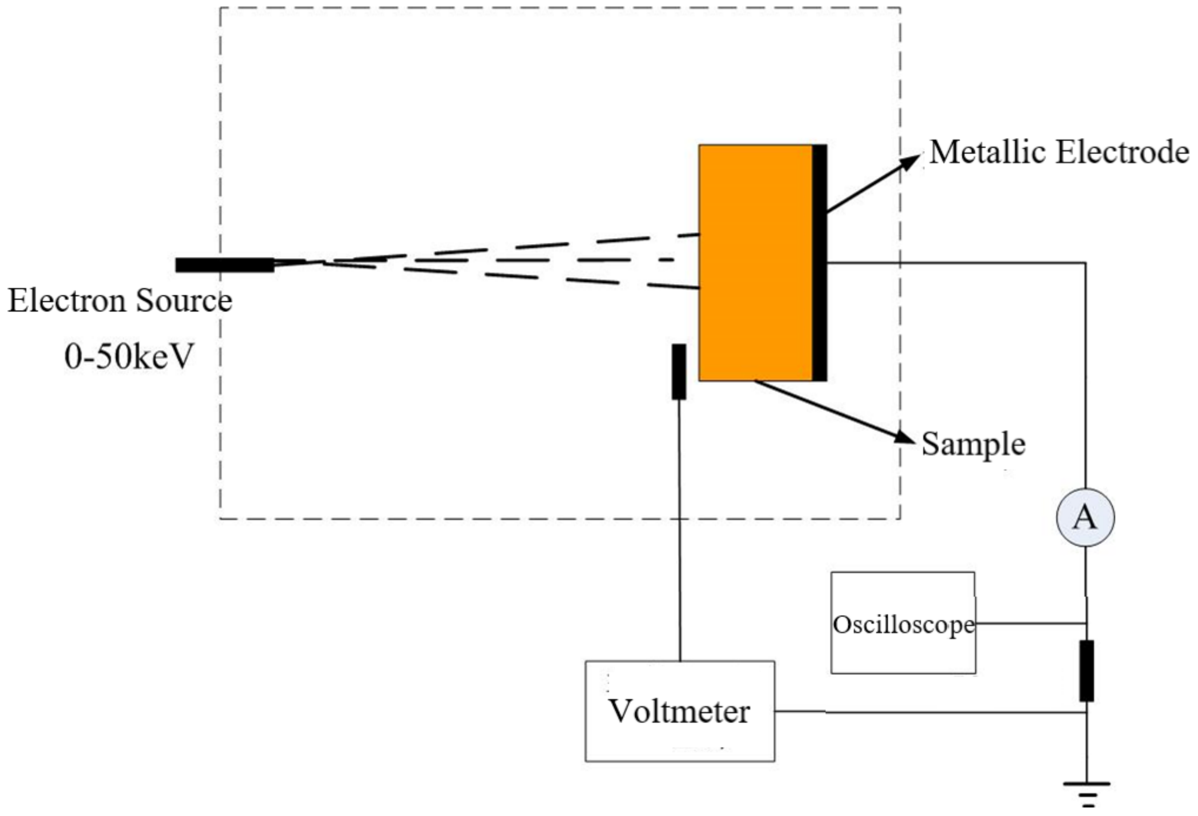
2 Phenomena

3 Geant4-RIC

4 Ground Experiment

Ground Experiment

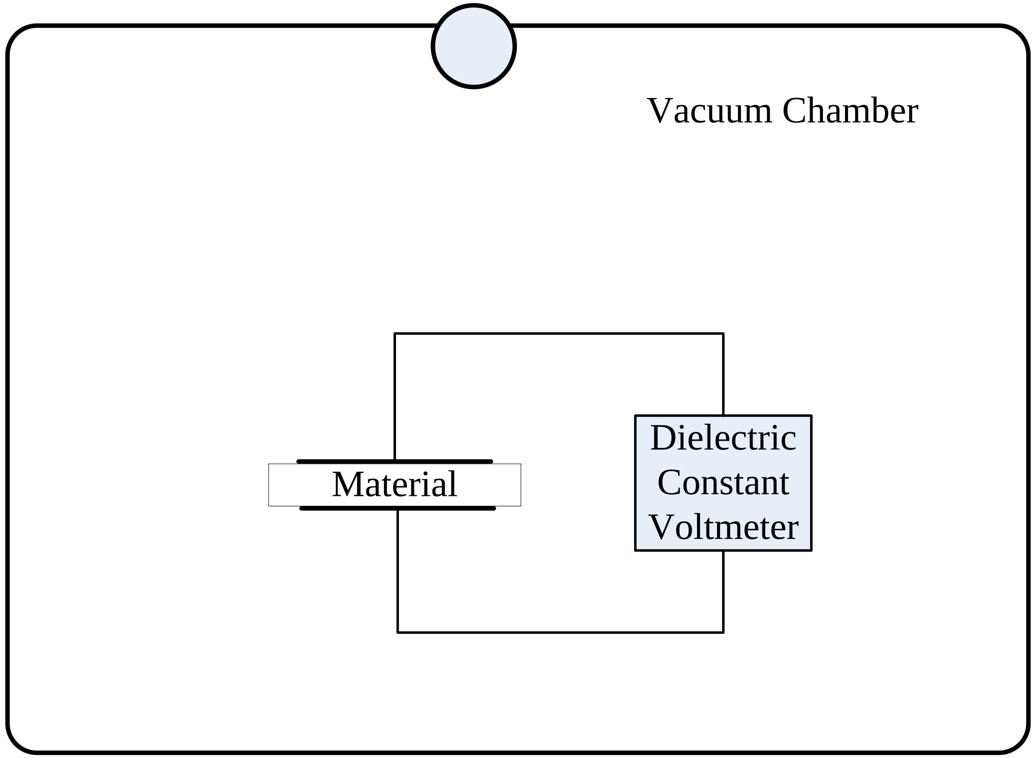
- Energy： 30KeV
- Current： 1600pA/cm^2
- Radiation dose:10M, 25M, 30Mrad
- Sample： Polyimide
- Sample Thickness: 50um
- Temperature： 300K



Ground Experiment

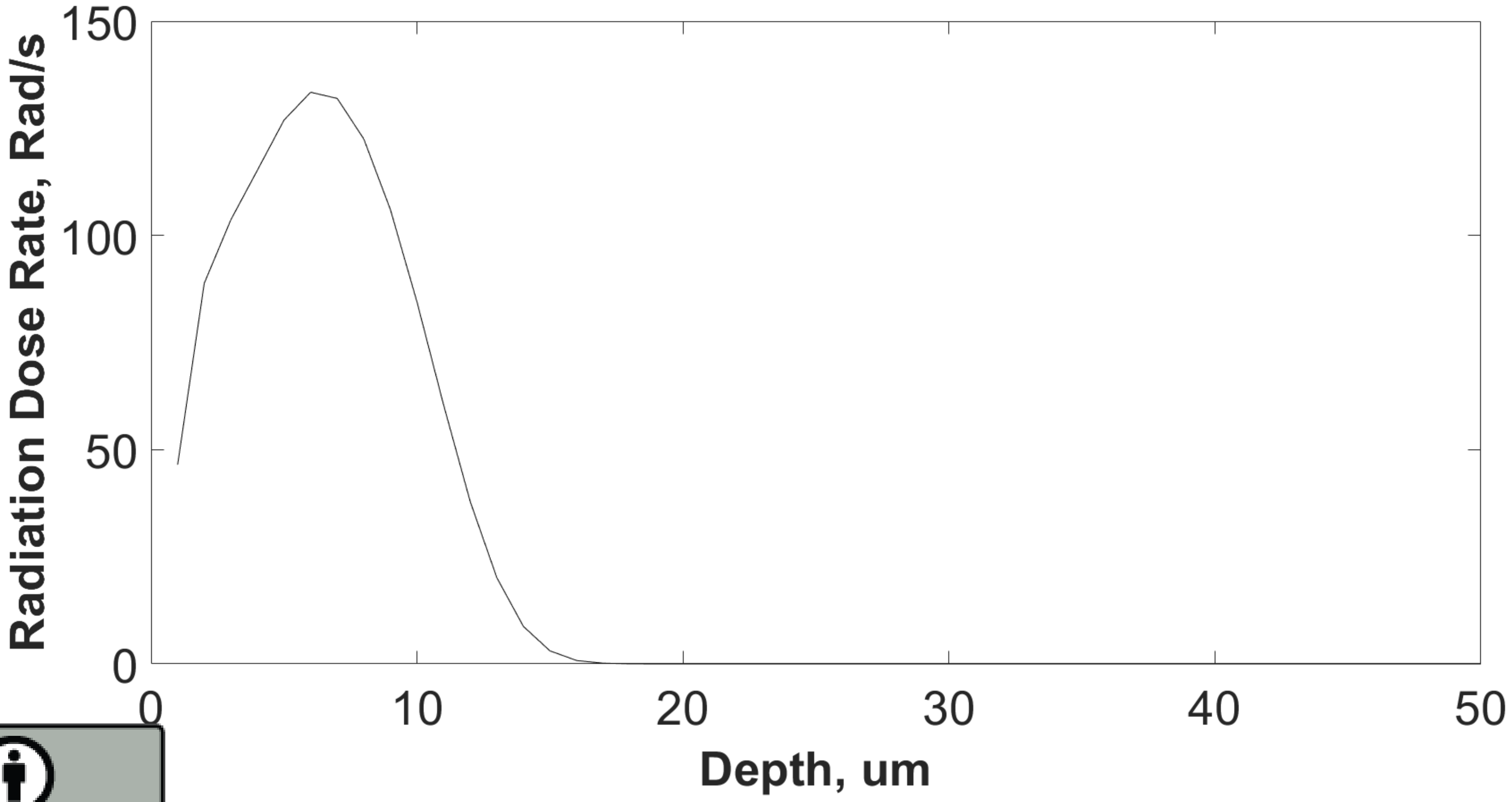
- Three same samples was exposed to different radiation dose.

- The relative permittivity of the sample was measured after the charge and discharge process finished.



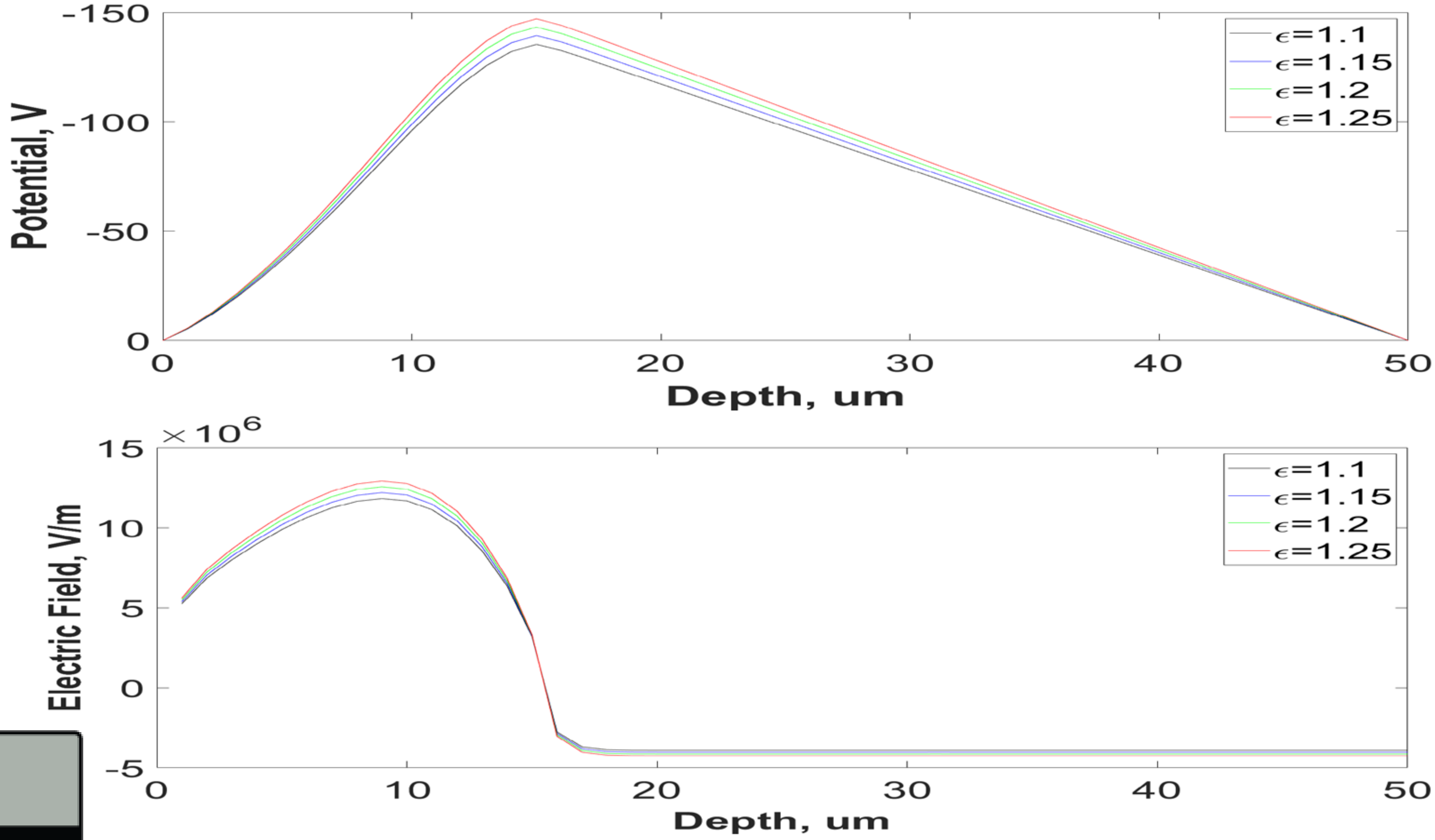
Results

The result of the Geant4 – RIC simulation



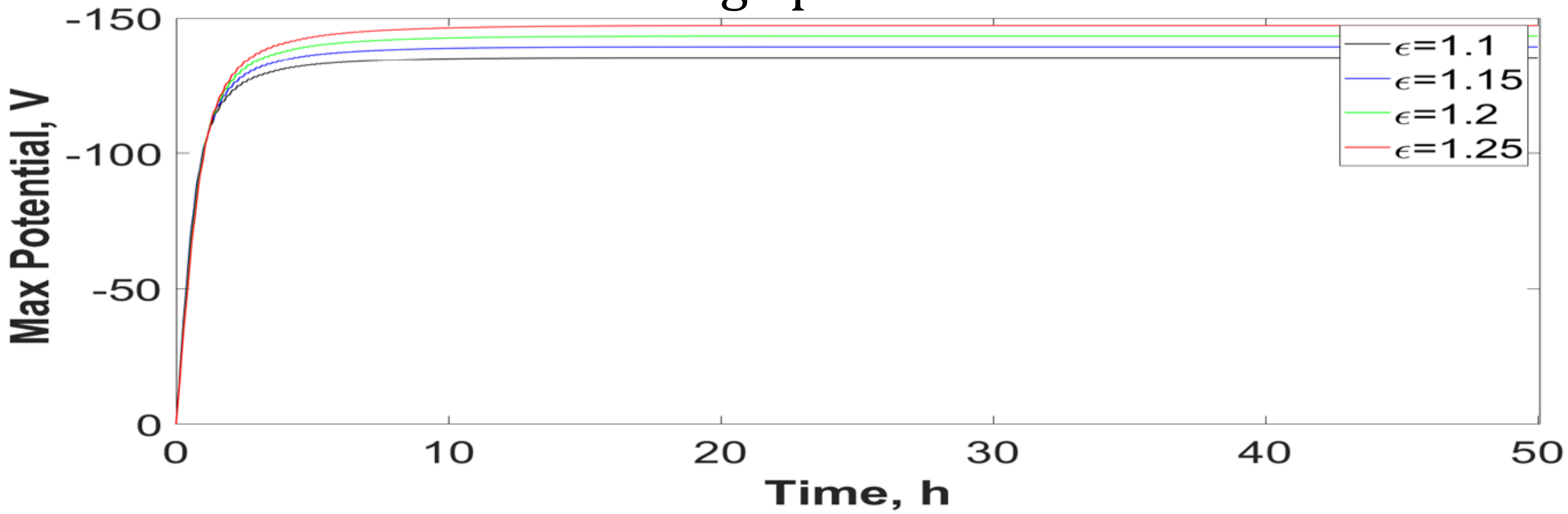
Results

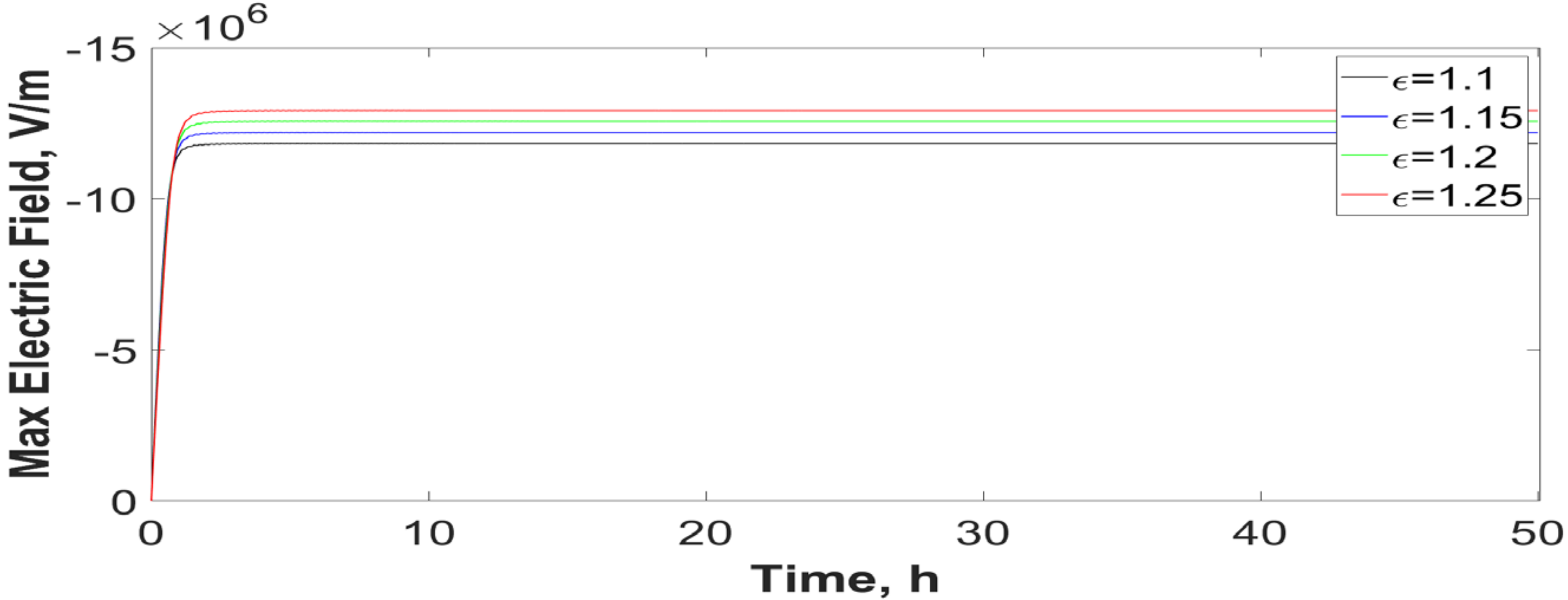
The charge process



Results

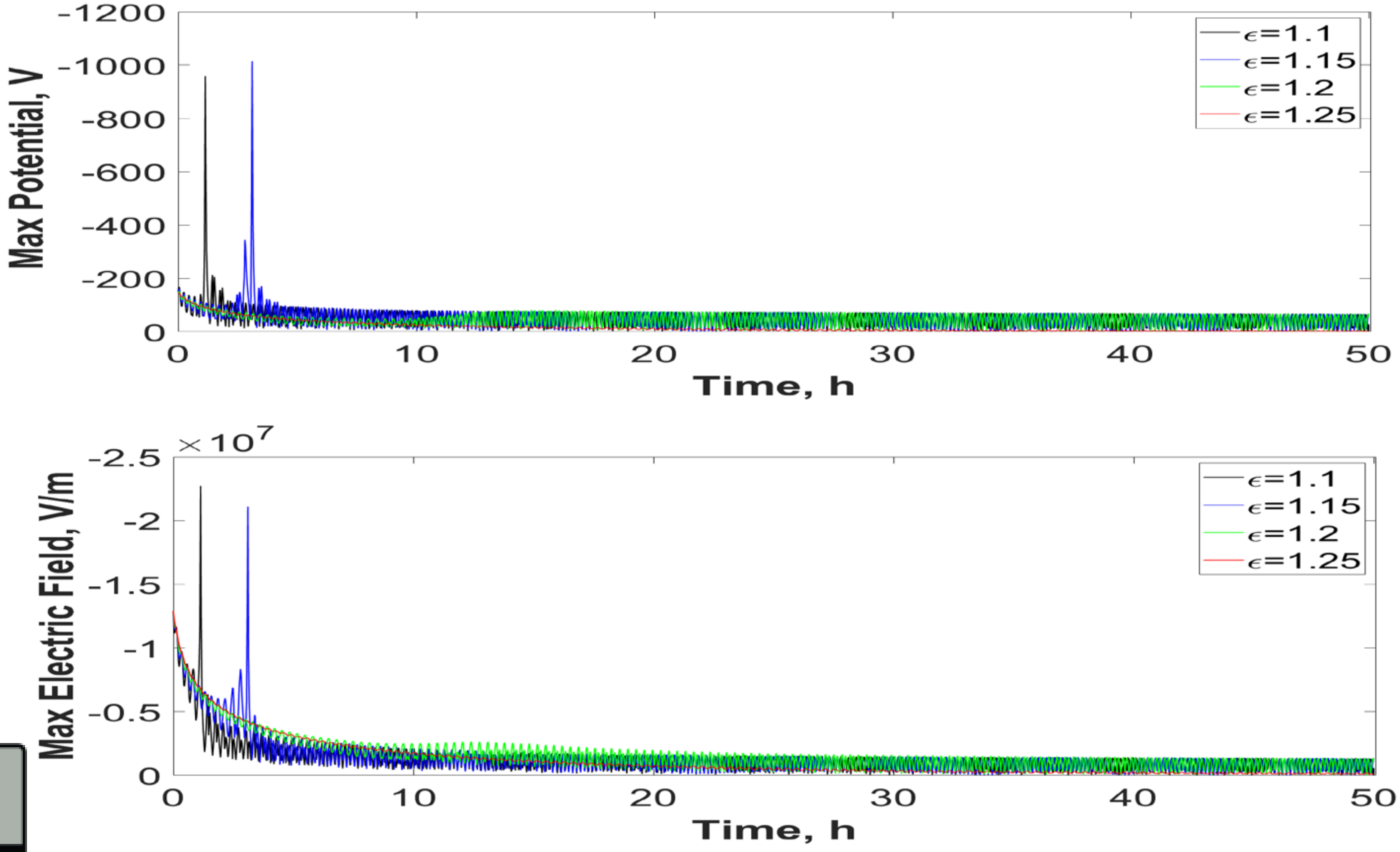
The charge process





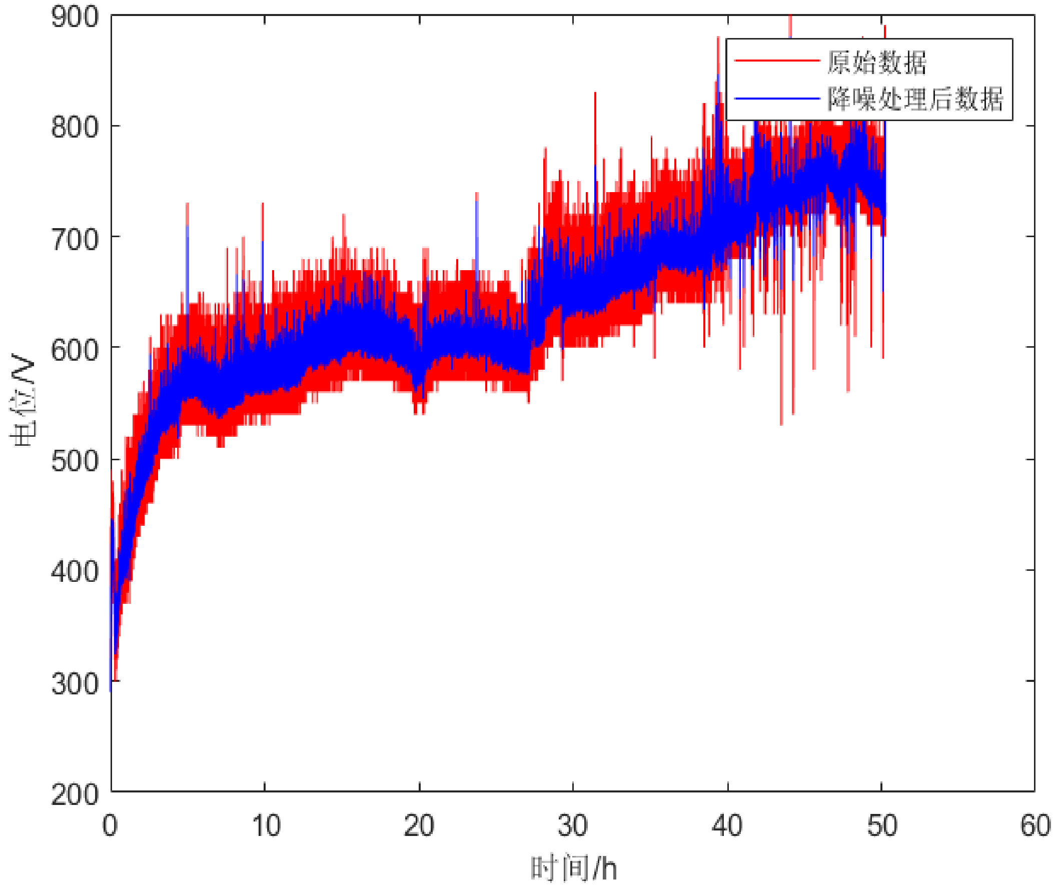
Results

The discharge process

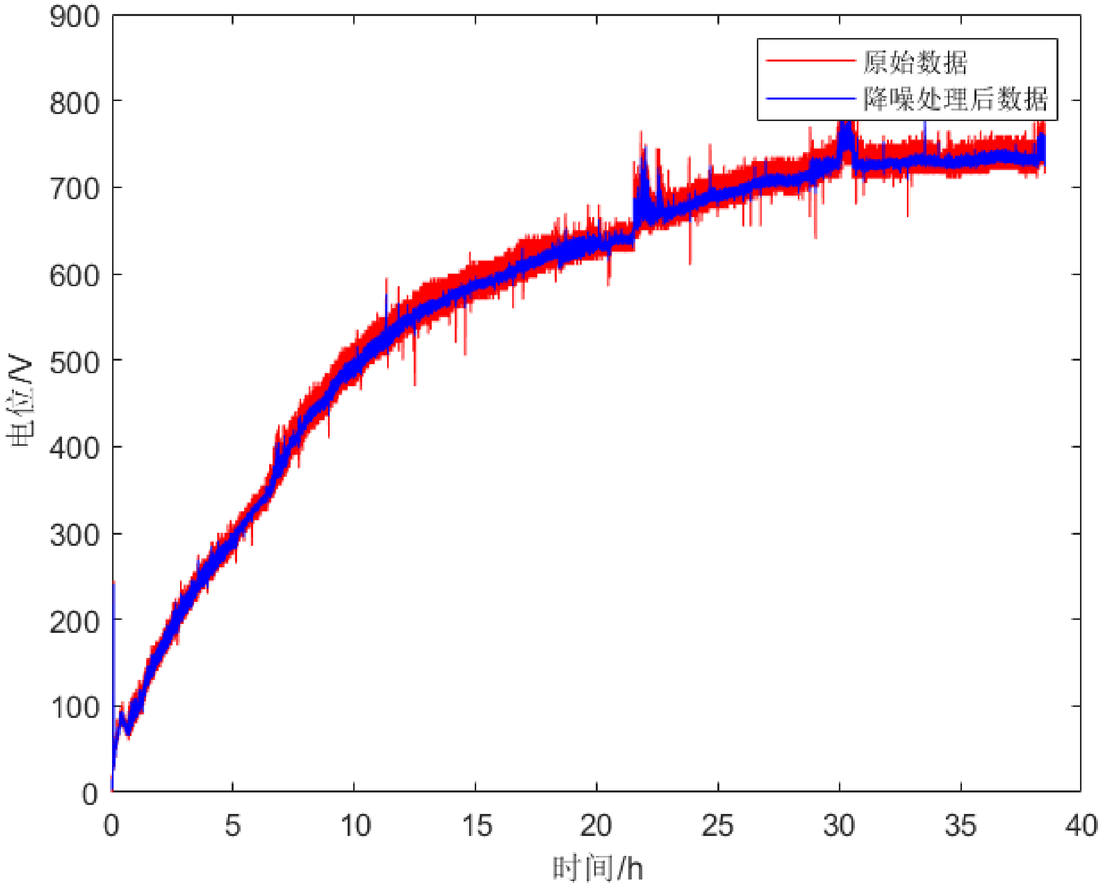


Results

The result of the ground experiment



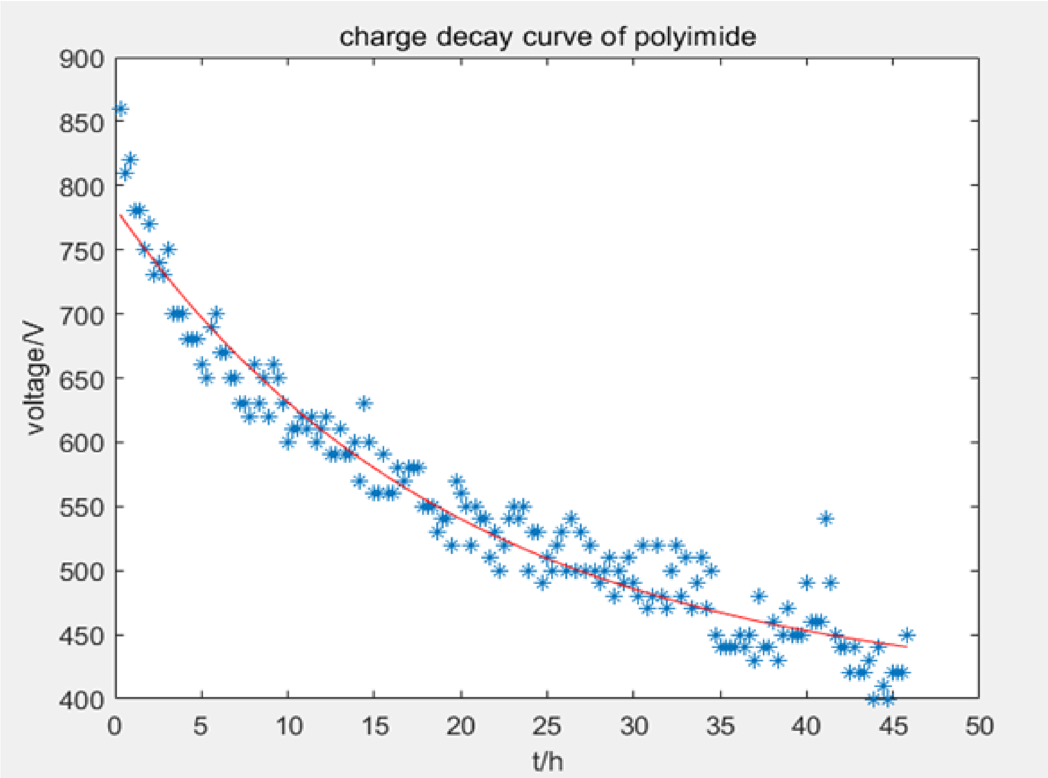
10Mrad irradiation



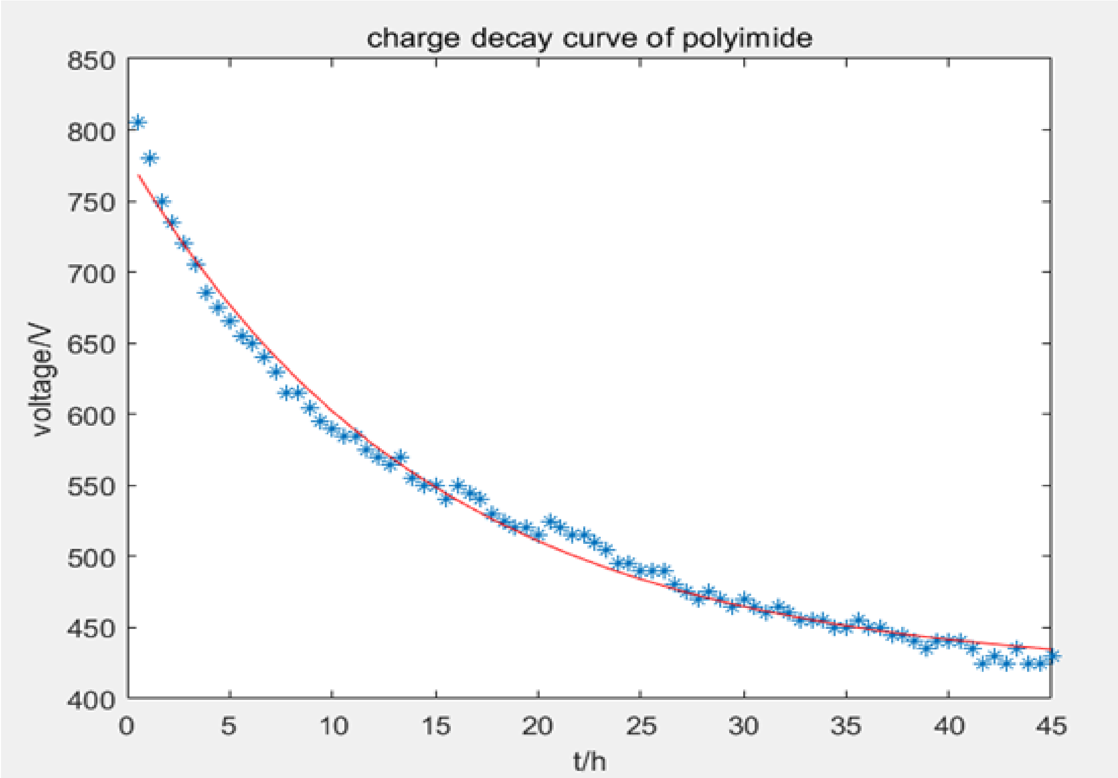
30Mrad irradiation

Results

The result of the ground experiment



After 10Mrad irradiation, the time constant τ =19.1h

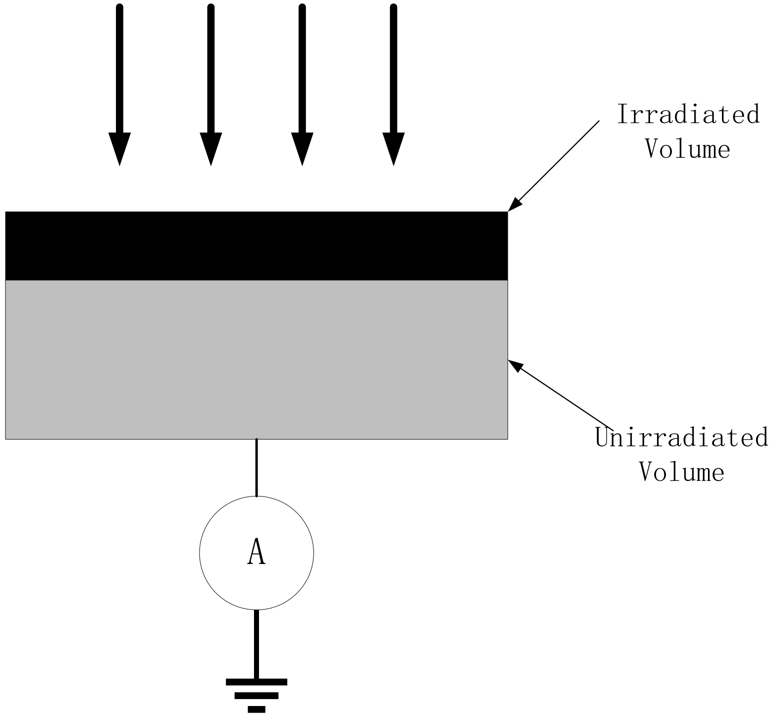


After 30Mrad irradiation, the time constant τ =14.7h

Results

The result of the ground experiment

Dielectric thickness/um	Radiation dose/Mrad	dielectric constant ε^*	$\frac{1}{\varepsilon^*}-\frac{1}{\varepsilon}$
50	0	1.250	0
50	10	1.207	0.02
50	25	1.129	0.06
50	30	1.093	0.08



Results

The change of relative permittivity of each layer may be:

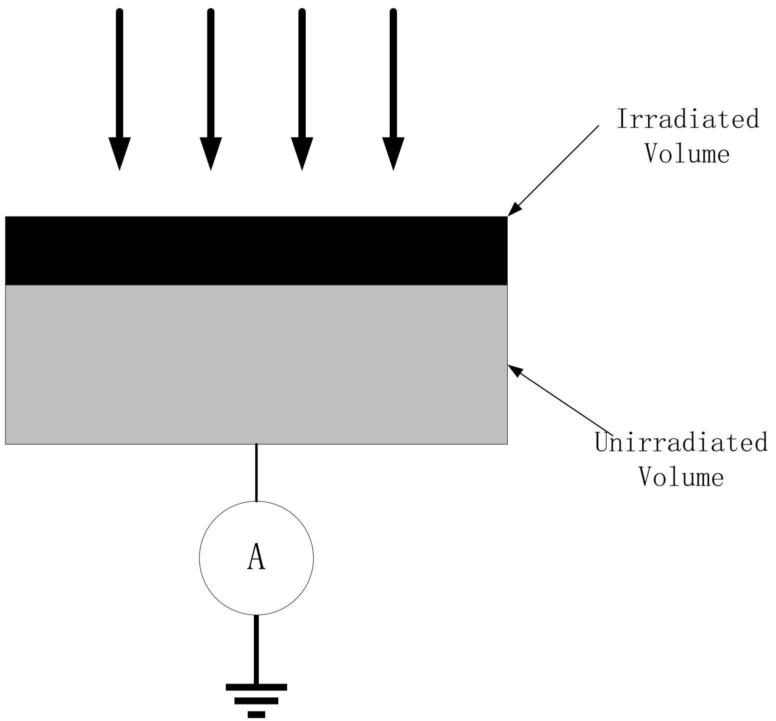
$$\varepsilon_i = \frac{\varepsilon}{1 + kD_i^{\Delta}}$$

The sample can be treated as 50 series capacitor:

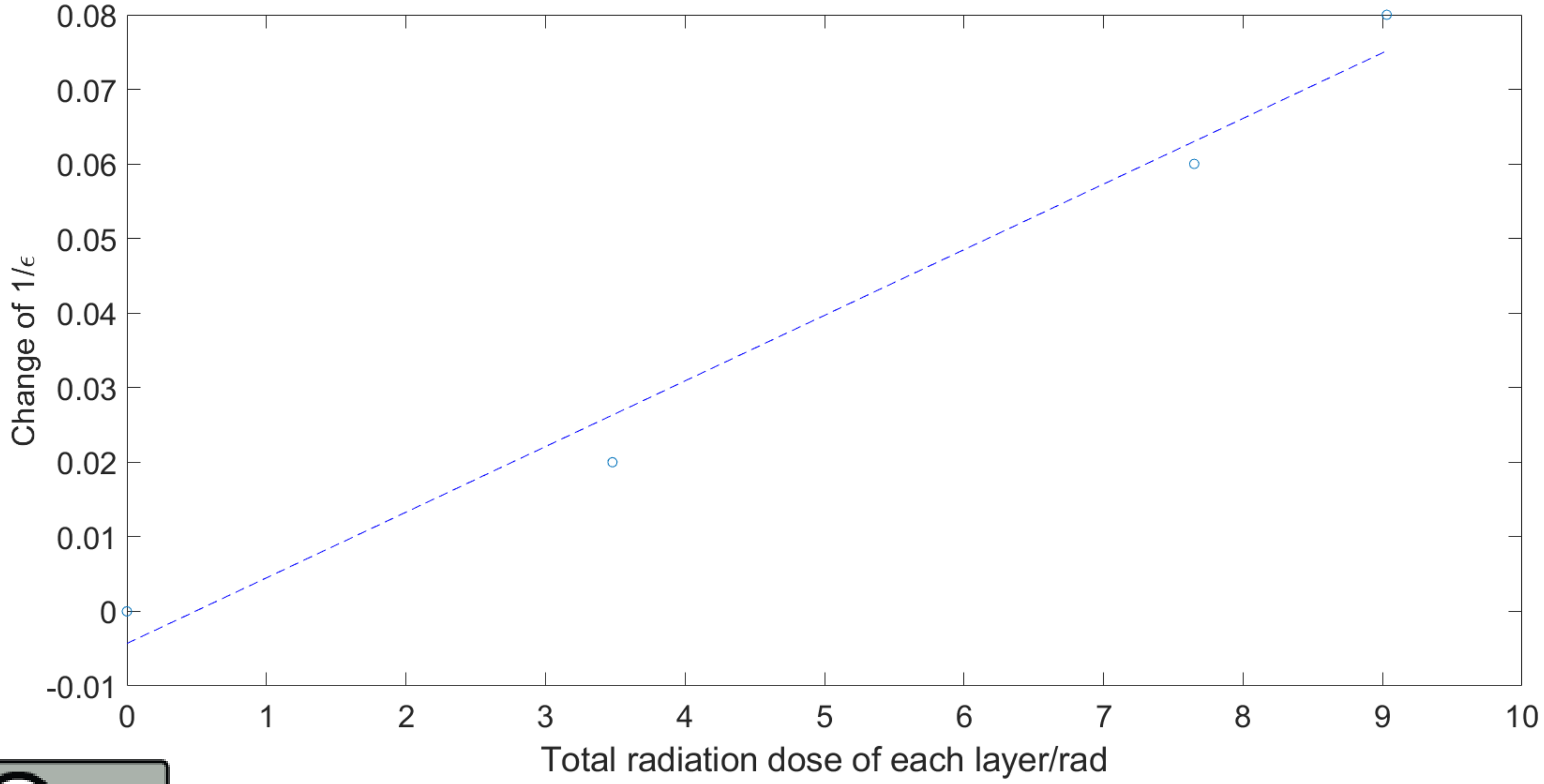
$$\frac{d}{\varepsilon_0 \varepsilon^* A} = \sum_{i=1}^{50} \frac{d}{n\varepsilon_0 \varepsilon_i A}$$

The change of total relative permittivity:

$$\frac{1}{\varepsilon^*} - \frac{1}{\varepsilon} = \frac{k}{n\varepsilon} \sum_{i=1}^{50} D_i^{\Delta}$$



Results



0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
Change of 1/ε
0
1
2
3
4
5
6
7
8
9
10
Total radiation dose of each layer/rad

Conclusion

- The relative permittivity of Polyimide decreased with the increase of total radiation dose.
- The time constant of discharge differs from the total radiation dose received.
- More parameters may be affected by the radiation dose, such as dark conductivity.
- More experiments on different dielectric materials will be carried out when the Covid-19 ends.

Thanks for listening!