Observations on Ion Track Structure in Semiconductors: A Phenomenological Study†

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***Abstract*-An ion track structure model at the nanometer scale is presented. The model is based on electrostatic principles and is supported by observed experimental results conducted on power MOSFETs. The model predicts the existence of a transient induced electric field following the passage of an energetic heavy ion. There are two segments to the field (a radial and an axial component). It is the interaction of this transient electric field with the local environment that can trigger a catastrophic failure.**

I. INTRODUCTION

For nearly a century, researchers have studied the phenomenon of energy deposition by the passage of an energetic heavy ion through a target medium both theoretically and experimentally [1,2, 3]. In recent years, however, there has been a large increase in research related to ion track structure at the nanoscale [4,5,6,7]. Researchers have long established that energetic heavy ions transfer considerable amount of energy to the electrons and nuclei of the target medium in the form of excitation and ionization. Ionization of the target atom leaves the atom with a net positive charge. During the brief moment of their existence, a cluster of positively charge atoms will produce a transient electric field. This transient field will interact with the local non-ionized atoms and may ionize them if conditions are right.

The existence of an electric field prior to the ion strike can have a major influence on the effect of the ion strike. For example, the presence of an electric field prior to ion strike can lead to SEGR or SEB (if the pre-field is large enough) [8 –15]. In Radiation-Induced Soft Breakdown (RSB) and Radiation-Induced Leakage Current (RILC) no pre-field is needed to rupture the oxide. RSB and RILC are strictly ion and ion energy dependent phenomenon. In this paper we present a track structure model which may be the 1st steps in attempting to explain the above phenomenon and perhaps others.

II. BACKGROUND THEORY

From principles of classical electrodynamics the energy that is transferred form a traversing ion to the target's atomic electron can be determined (or at the very least estimated). Assume that the incident particle has a velocity of V, mass M (where M is much greater than the rest mass of an electron), and kinetic energy of the traversing ion is equal to γMc^2, where $\gamma = (1-\beta^2)^{-1/2}$. The incident ion with a charge of Z_1 passes by a stationary atomic electron (of charge –e) at an impact parameter distance of b. The energy transferred to the atomic electron is

$$\Delta E = \frac{(\Delta p)^2}{2m_e} = \frac{2Z_2^2 Z_1^2 e^4}{b^2 V^2 m_e} \tag{1}$$

where Z_2 is the target's atomic charge. The energy transferred varies as an inverse square of the impact parameter (b), therefore, close collisions yield large energy transfer (up to ΔE_{max}). The maximum energy that can be transferred corresponds to a head-on collision. The maximum energy transfer is

$$\Delta E_{\max} = 2m_e V^2 \gamma^2 (1 + 2\gamma \frac{m_e}{M} + \frac{m_e^2}{M^2})^{-1} \tag{2}$$
$$\cong 2m_e V^2 \gamma^2 .$$

The maximum energy transfer is independent on Z of either target atom or incident ion; it is dependent on the ion's velocity squared. The energy transfer is independent of M ($m_e/M \sim 0$). In addition to energy transfer, the ion will acquire electrons as it slows down due to interaction with the medium, this phenomenon is termed effective charge (Z_{eff}). The effective charge used in this paper comes from the empirical formula derived by Barkas [16],

$$Z_{eff} = Ze(1 - \exp(-125\,\beta Z^{-2/3})). \tag{3}$$

In the above equation, *e* is the fundamental unit charge, β is the relativistic ion speed (v/c) and Z is the total charge of the ion's nucleus.

III. DELTA-RAYS

Delta-rays (δ-rays) deposit their energy through multiple collisions with the target's atomic electrons. Figure 1, shows the expected range of δ-rays as a function of kinetic energy for Si and SiO_2 as the target mediums. The data used in figure 1 comes from Hamm [17] and Kim [18]. Hamm's data, which ranges from 7 up to 10^4eV, was digitized and added to the data set from Kim. Kim's data set covers the

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range from 10^4 up to 10^9eV. The data is displayed in figure 1 without any manipulation of the data sets. Both data sets merge smoothly between the range of 10^2 to 10^6eV. The best fit lines adheres to a power law formula [19] of the form

$$r(cm) = kE(eV)^n \tag{4}$$

The values for the above parameters are as follow,

Si: ~49eV $\leq$ E $\leq$ 10^5eV, n = 5/3, k = $1x10^{-10}$

SiO_2: 100eV $\leq$ E $\leq$ 10^5eV, n = 5/3, k = $1x10^{-10}$

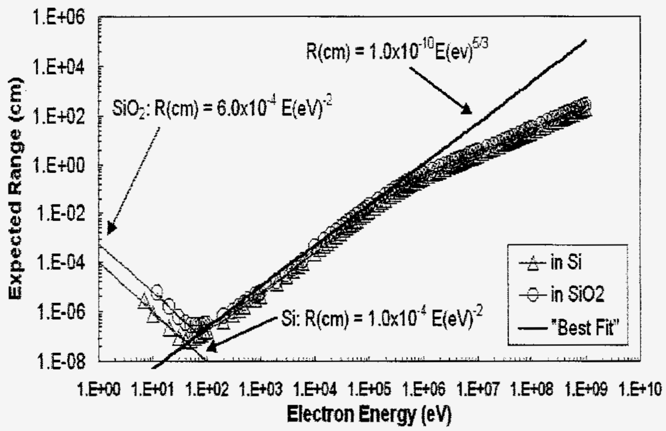

Figure 1: Expected δ-ray range as a function of kinetic energy (eV).

Above 10^5eV the expected range for electrons decrease due to the production of Bremsstrahlung radiation. At low kinetic energies (<100eV), the electron range increases due to interactions with electrons in the conduction band. For kinetic energies under 100eV, we fitted the data with another power law, whose n and k are as follows,

Si: 3.6eV $\leq$ E $\leq$ ~40eV, n = -2, k = $1x10^{-4}$

SiO_2: 9eV $\leq$ E $\leq$ ~50eV, n = -2, k = $6x10^{-4}$

The energy distribution for δ-rays is obtained by modifying equation (1) with equation (3). For a given target thickness, the total number of δ-rays produced (N) with energies > ΔE_{min} and < E, is given the following formula,

$$N(\Delta E_{\min} \leq E \leq \Delta E_{\max}) = \int \xi \frac{dE}{E^2} = \xi\left(\frac{1}{E} - \frac{1}{\Delta E_{\max}}\right) \tag{5}$$

where E $\leq$ ΔE_{max}, and ξ is $(2\pi n_e Z_{eff}^2 e^4)/m_e V^2$, n_e is the number of electrons per unit volume, m_e is the electron rest mass, and V is the velocity of the ion.

A large number of low energy δ-rays are created when β = 0.05 and 0.1 (arbitrarily chosen). The weighted average kinetic energy of a δ-ray at β = 0.05 was determined to be 20.2eV for two ions, Xe and Ne. At β = 0.1, the weighted average was 25.1eV for both ions. This result indicates that the average energy that is imparted by the ion to an electron is dependent on β, but independent of Z. An additional calculation was done to determine the weighted average angle of ejection (θ). The angle of ejection was calculated by using the Rutherford scattering relationship,

$$\cos^2(\theta) = \frac{E}{\Delta E_{\max}} \tag{6}$$

on average the δ-rays are ejected angle of ~90° relative to the ion's path.

IV. TRACK-CORE INDUCED ELECTRIC FIELD

In Si the amount of energy needed to create an electron hole pair (ehp) is 3.6eV (in SiO_2 it is 9eV), combining equations 1 and 3 and then solving for b, the expected radius of an ion track can be calculated. Therefore, the core diameter of a ion track is

$$d(nm) = Z_{eff} \frac{5.697x10^{-3}}{\beta\sqrt{\Delta E(eV)}} \tag{7}$$

The length of the ion track is dependent on the lifetime minority carrier and the doping concentrations in the environment around the track-core.

Based on electrostatics principles, an infinite cylinder of charge q will induce a radial electric field that falls off as r^{-1}. The radial electric field from a finite cylinder of length 2L and charge q, falls off as $[r(r^2+L^2)^{1/2}]^{-1}$ for radial distances in the order of L, if r >>L, the field falls off as r^{-2}. The axial electric field inside an infinite cylinder of any diameter is zero, but for a finite cylinder of length L, the axial field is not zero. The solution is given by the infinite series given by (8). Figure 4 shows the result of a numerical computation for an ion track-core diameter of 0.7nm and a length of 32nm. The ion is incident on a silicon diamond crystal structure.

$$V(x_i) = \sum_{\substack{j=1 \\ j \neq i}}^{n} \frac{1}{4\pi\varepsilon\varepsilon_0} \frac{q_i}{x_{ij}} \tag{8}$$

where n is the number of ionized atoms in the track-core, q_i is the i^{th} ionized atom, ε and ε_0 are the permittivity of the target medium and of free space, respectively. The computed ion induced potential ranged from 140 to 225 volts, see figure 2.

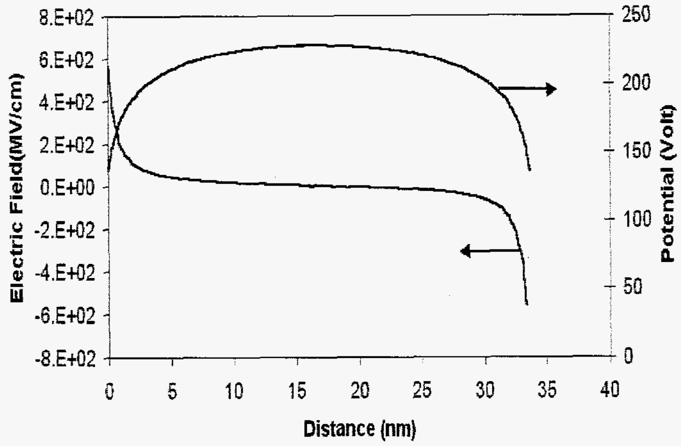

Figure 2: Axial electric field and potential induced by an ion whose track core diameter is 0.8nm and 32nm long incident on silicon crystalline structure.

The axial electric field induced by the track structure is symmetrical about the center of the cylinder. The maximum field strength takes place at the ends of the cylinder. The intensity of the axial electric field are high, however, the time scale in which they occur last somewhere in the order of several hundred picoseconds, according to results provided by PISCES (a commercial software package). An ion can traverse a 75nm oxide in < 10femtoseconds [L. Selva]. The transient field can last 10,000 to 100,000 times longer than the passage of the ion.

V. Energy Density

The energy used in assembling a crystal is stored in the electric and magnetic fields, which fill the space between the particles. In this discussion we assume zero magnetic contribution. The energy density over the discrete space is given by the following formula,

$$w = \frac{1}{2}\sum_{i=1}^{n} q_i V(x_i) \tag{9}$$

For the ion track structure used in figure 4, the energy density (store energy) was calculated to be 23eV per atom. The energy needed to remove a matrix atom from silicon is less than 5eV. In other words, there is enough energy stored in the system to destroy the order crystal structure.

Assuming a continuous charge distribution inside the track-core and after some vector algebra manipulation, equation (9) transforms into the following

$$w = \frac{\varepsilon\varepsilon_0}{2}\left[\int_{surface} V\vec{E}\bullet d\vec{a} + \int_{volume} E^2 d\tau\right] \tag{10}$$

where V is the surface potential, E is the electric field vector, da is the normal pointing vector of the elemental surface area and dτ is the elemental volume. By restricting our attention to the track-core, the first integral can be ignored. By incorporating a pre-existing electric field (E_{pre}) with the track-core induced electric field (E_{ind}) and converting the energy density into an energy density differential, which is a measure of the stored energy per unit volume, equation (10) becomes

$$k\frac{dw}{d\tau} = E_{pre}^2 + E_{ind}^2 + 2E_{pre}E_{ind}\cos\theta \tag{11}$$

k is ($2/\varepsilon\varepsilon_0$) and θ is the angle between the electric field vectors.

VI. Experimental Results

SEGR and SEB experiments were performed on several devices, they are listed in tables 1 and 2. Some of the MOSFETs were irradiated under reverse bias condition in order to produce parallel but opposing fields within the oxide during the ion strike. According to equation (11), parallel fields and parallel but opposing fields have the same E_{pre} solution. Results confirmed the prediction. Three device types were tested, including a few p-channels devices, see table 1. The IR2N6782, by International Rectifier was used to explore the angular dependence of SEGR, the results are shown in figure 3. In order to use equation (11), it was assumed that the ion induced electric field had a value of 20MV/cm (this is a reasonable assumption considering it takes < a few picoseconds for the maximum field strength to decay based on results from PISCES). The two ions used were I^{127} at 350MeV and Br^{79} at 276MeV, the onset of SEGR at 0° was calculated to be 5.0 and 6.3MV/cm, respectively. Accordingly, the critical differential energy density, k(dw/dτ), for SiO_2 was estimated to be 625J/m^3.

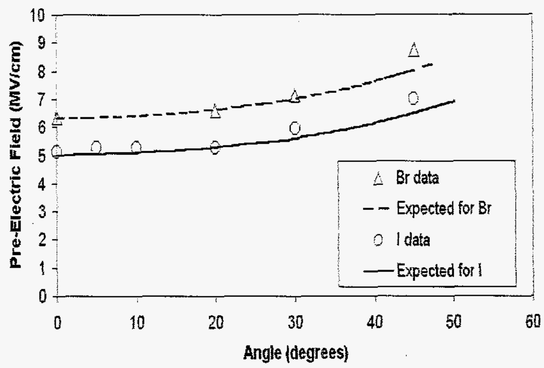

Figure 3: Experimental results for the angular dependence of SEGR along with the predictive values using equation (12).

Table 1.
MOSFETs used to conduct SEGR experiments.

Manuf.	Model	N-ch	P-ch	Rating (V)
IR	IR2N6782	X		100
IR	IR2N6790	X		200
IR	IR2N6786	X		400
Siliconix	Si6544DQ	X*	X	30
Fairchild	NDS8958	X	X	30
Fairchild	NDS9945	XX*		60
Fairchild	NDS9936	XX		30
Fairchild	NDS8947		XX*	30

XX denotes dual MOSFETs in a single package.
* denotes device tested under reverse bias conditions.

Table 2.
PNP Transistors used to conduct SEB experiments

Manuf	Model	Rating (V)	Ion used
Zetex	FMMT558CT	400	Xe, Au
Semelab	2N5416	400	Xe, Au
NES	2N3743	400	Xe, Au
Microsemi	2N3743	400	Xe, Au
Fairchild	2N6519	400	Xe, Au

The energies for the ions used in table 2, were 3200MeV and 2955MeV for Xe and Au, respectively.

VII. CONCLUSION

In this paper we have presented a new phenomenological model for ion track structure and their effects on semiconductor devices. The model predicts the existence of a short lived and high intensity electric field generated by the track structure. Preliminary results support the model. However, additional experiments are needed to complete the data set.

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Outline

- Purpose: Phenomenology
- Theory :

  1) Delta-rays

  2) Track-Core: Electric Fields

  3) Energy Density: Energy Stored
- Experimental Results: Angular Dependence
- Conclusion

Purpose

Construct a model for ion matter interaction based on:

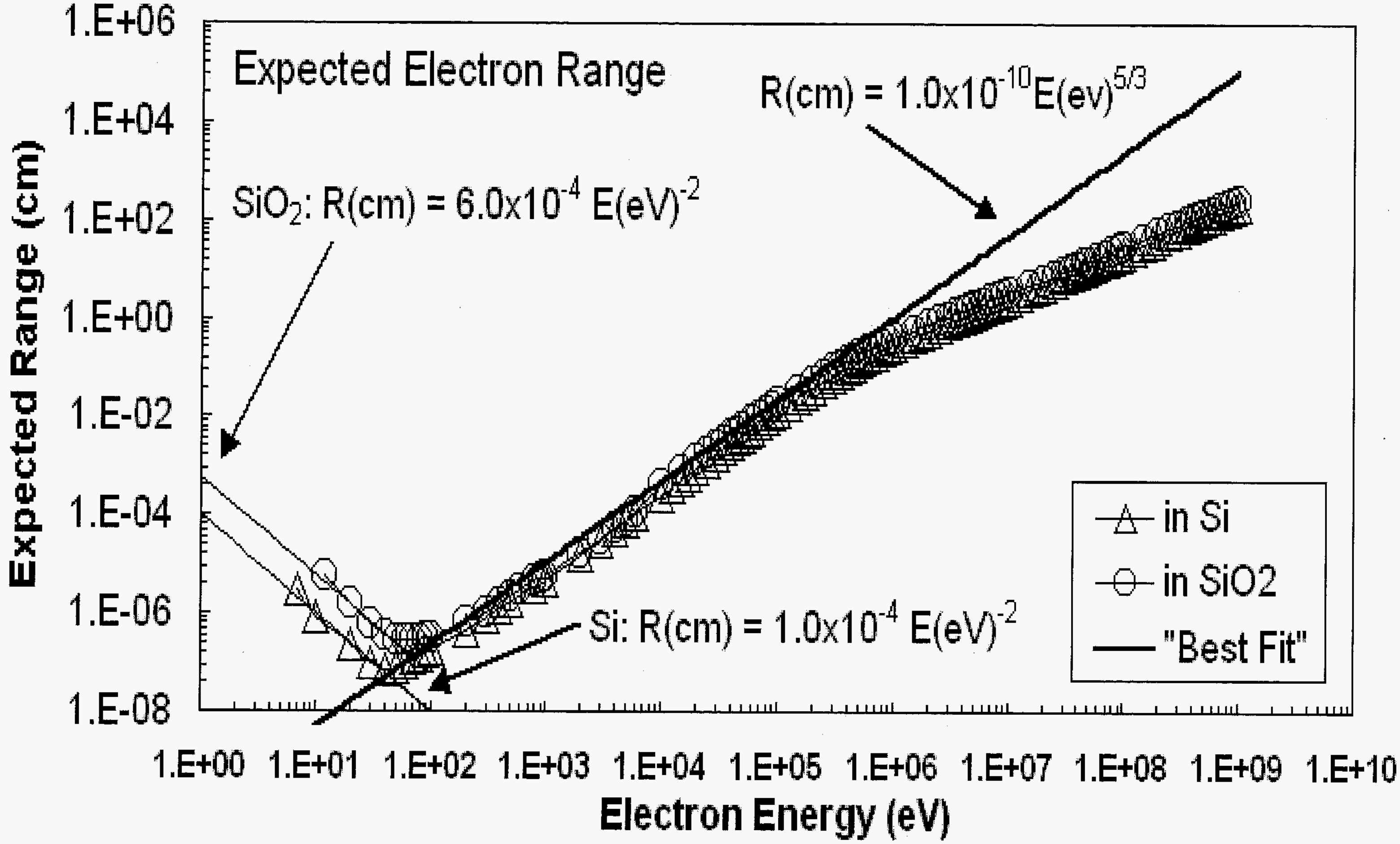
1)First principals

2)Phenomenological

Theory: Delta-rays

- Range is a f(ΔE)
- ΔE is a $f(z^2Z^2/V^2b^2)$
- Power Law

$$r = kE^n$$


Expected Electron Range
R(cm) = 1.0x10^-10 E(ev)^5/3
SiO2: R(cm) = 6.0x10^-4 E(eV)^-2
Si: R(cm) = 1.0x10^-4 E(eV)^-2
in Si
in SiO2
"Best Fit"
1.E+06
1.E+04
1.E+02
1.E+00
1.E-02
1.E-04
1.E-06
1.E-08
Expected Range (cm)
1.E+00 1.E+01 1.E+02 1.E+03 1.E+04 1.E+05 1.E+06 1.E+07 1.E+08 1.E+09 1.E+10
Electron Energy (eV)

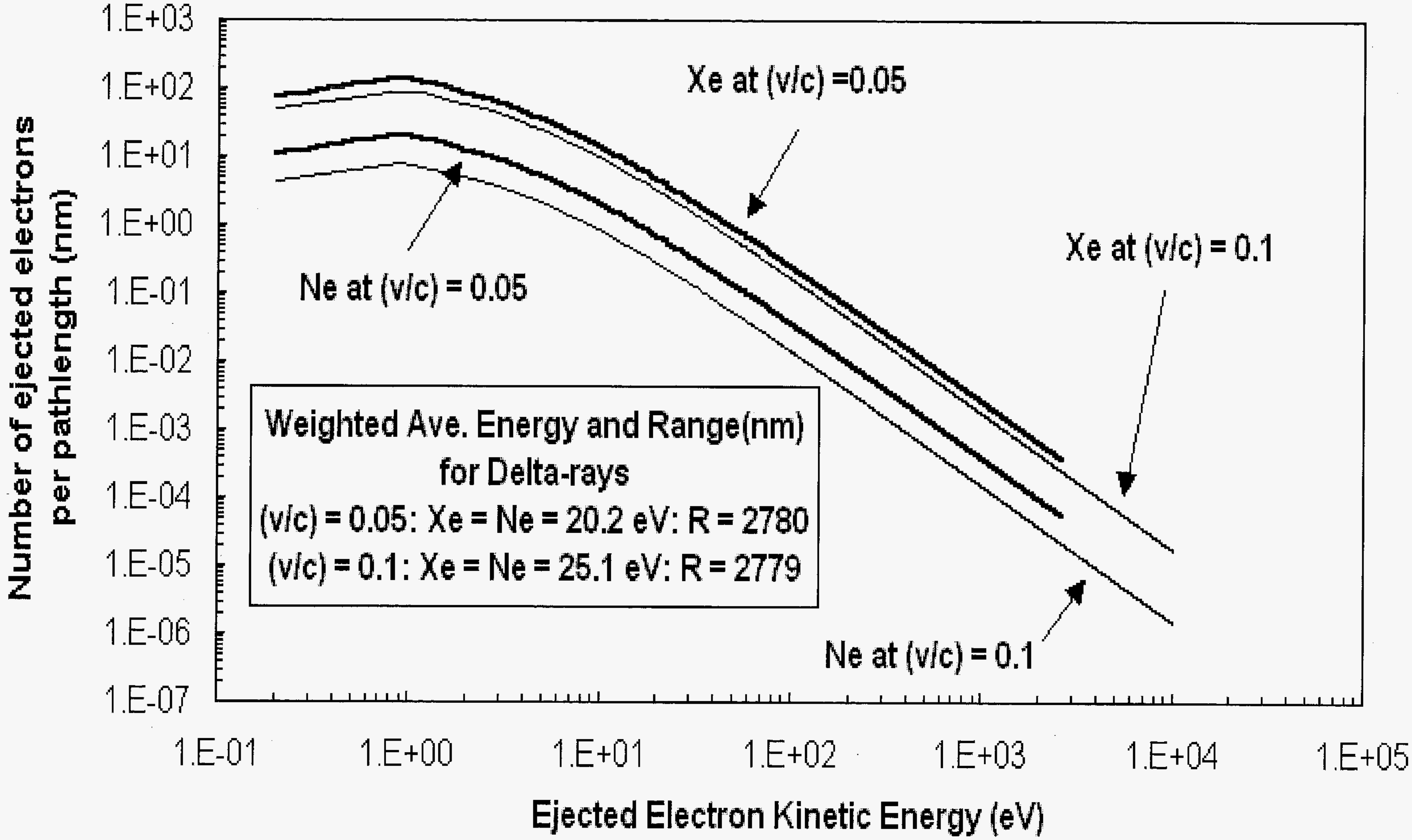
Theory:Delta-rays (continued)

- Delta-ray distribution:

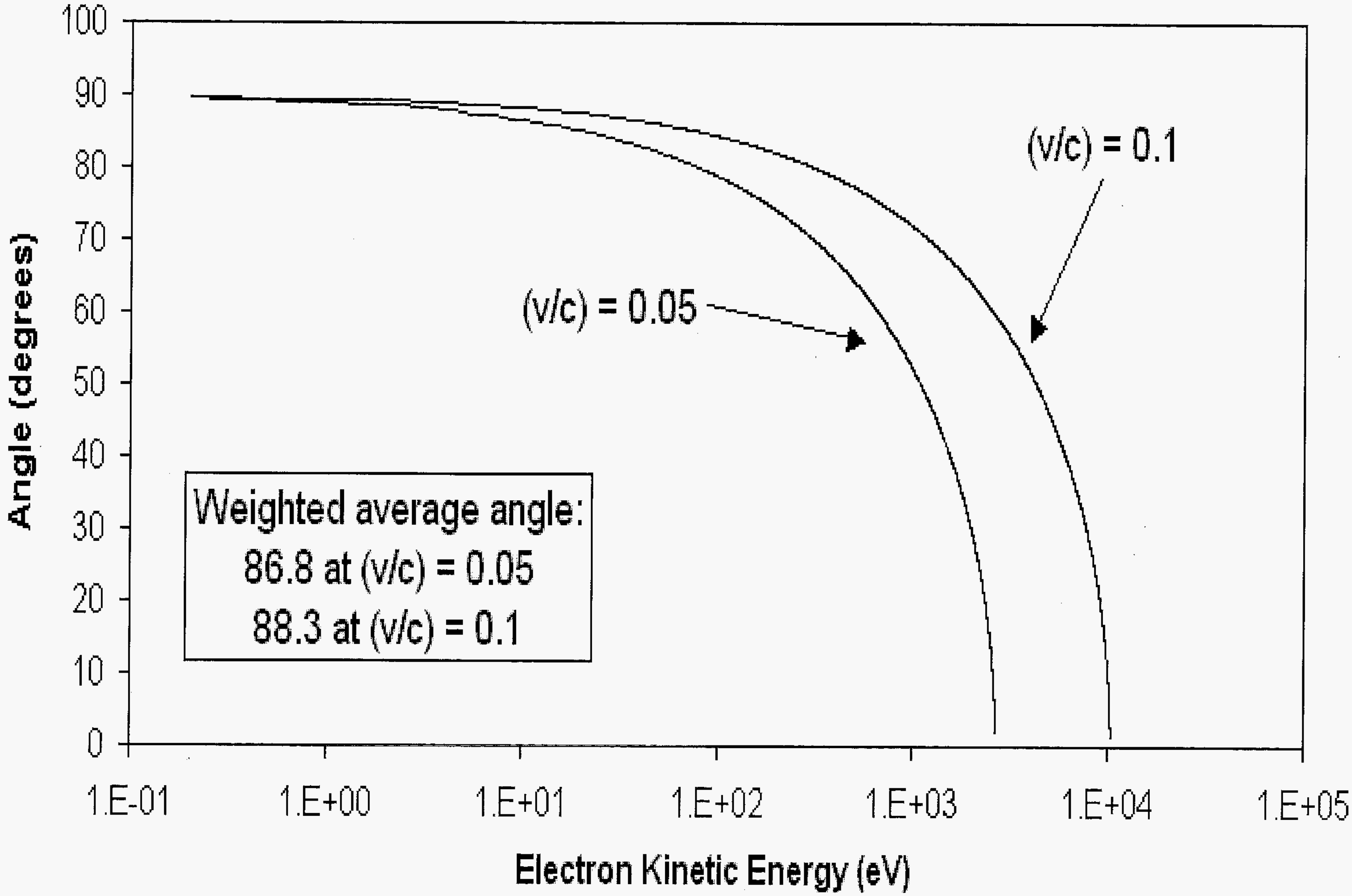
$$N = \int_{E}^{\Delta E_{\max}} \xi \frac{dE}{E^2} = \xi\left(\frac{1}{E} - \frac{1}{\Delta E_{\max}}\right)$$

- Graph Ne, Xe at (v/c) =0.05, 0.1
- Ejection angle ~90°

Delta-ray distribution



Angle of ejection



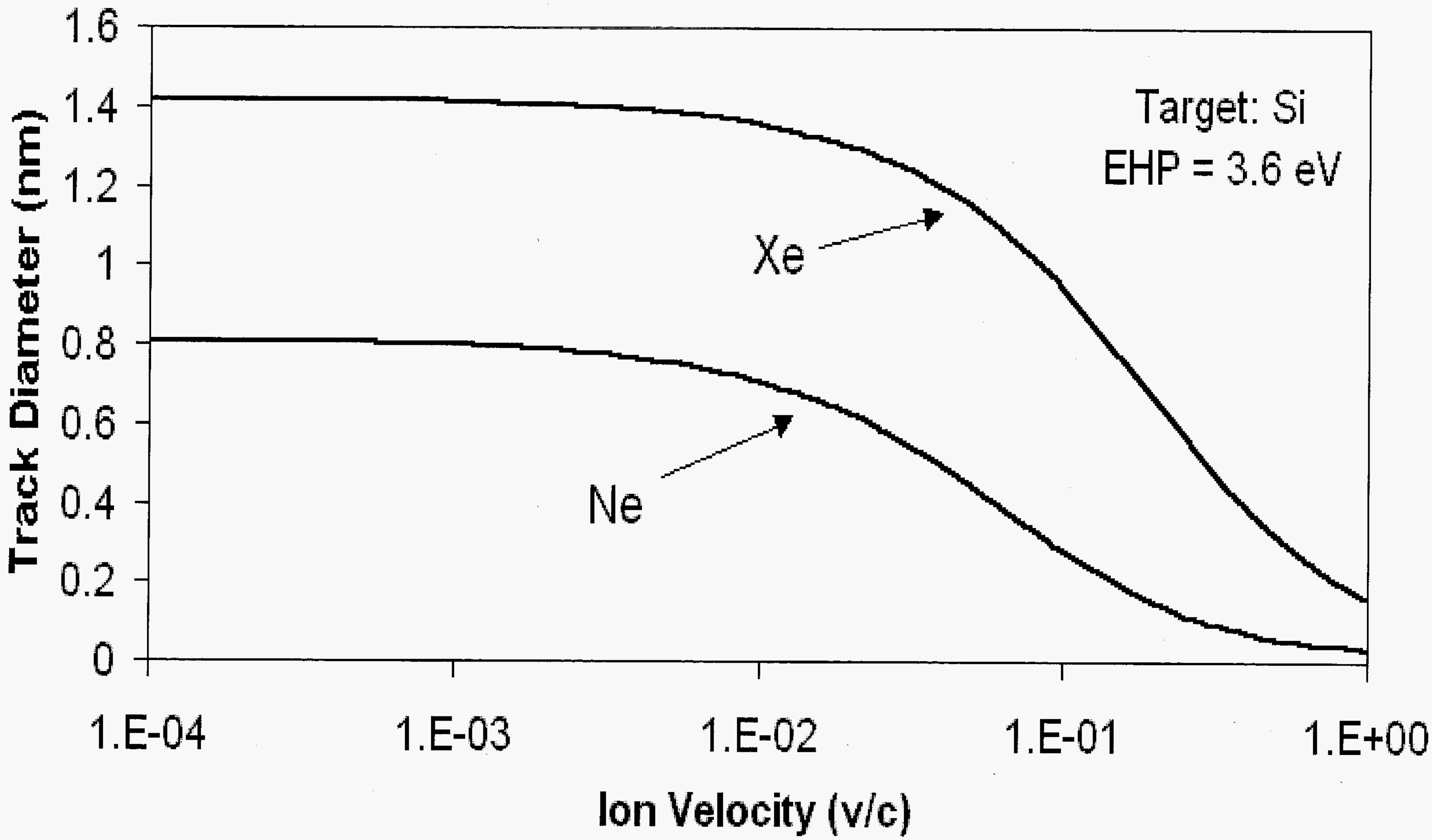
Track-Core

- Column of positive charges
- E&M diameter

$$d = Z_{eff} \frac{C}{\beta \sqrt{\Delta E_{\min}}}$$

- d is f(material, Z,and β) agrees with observed results

Ion Track-core diameter



Track-core

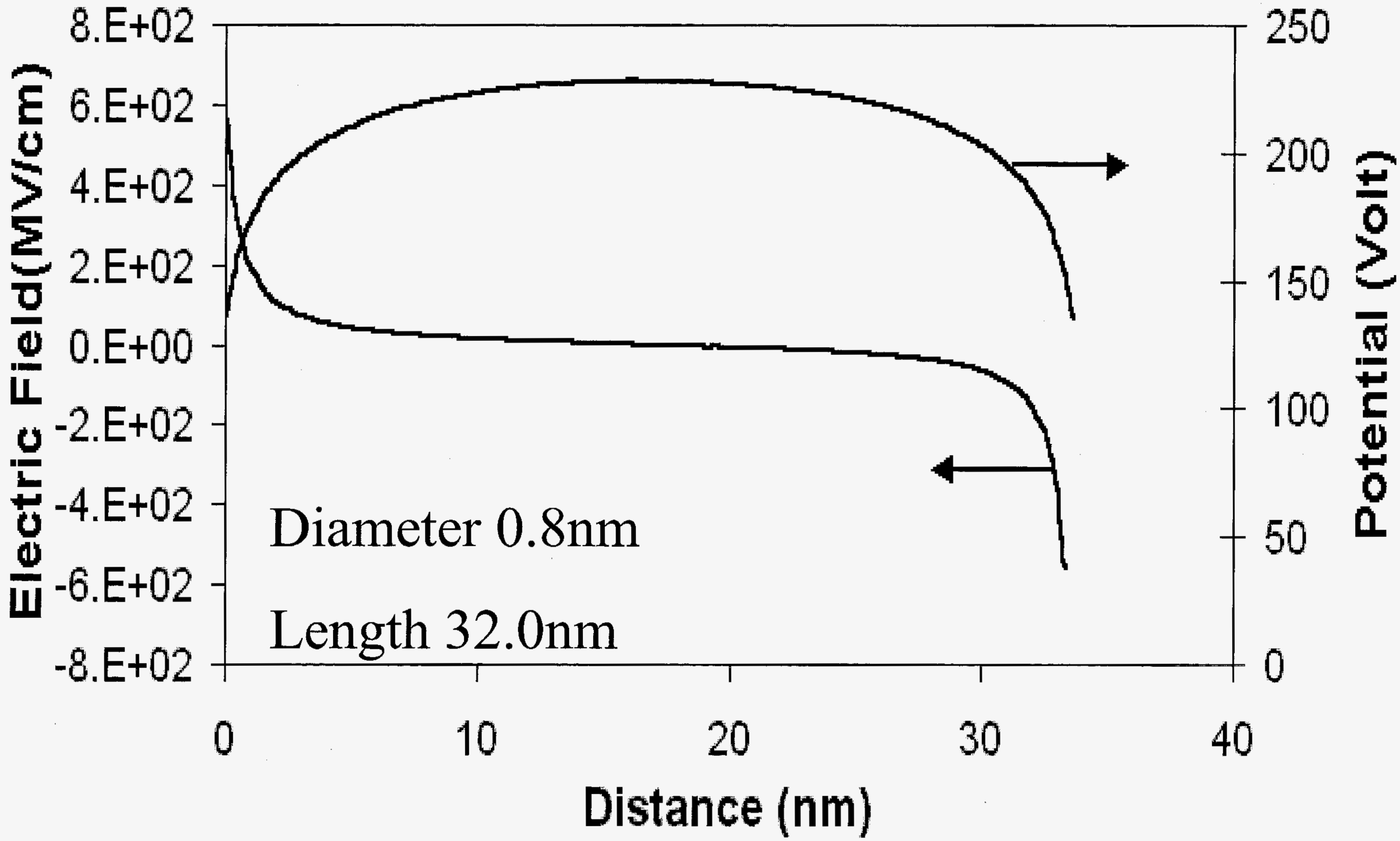
- Induced Potential

$$V(x_i) = \sum_{\substack{j=1 \\ j \neq i}}^{n} \frac{1}{4\pi\varepsilon\varepsilon_0} \frac{q_i}{x_{ij}}$$

- Induced Electric Field

$$\vec{E} = -\vec{\nabla} V$$

Induced Electric Field



Track-core (continued)

- Life-time issues:

  1) Q.M.: f(energy dif.) $\tau \approx 1\text{x}10^{-17}$ sec.

  2) Bulk minority carrier life-time

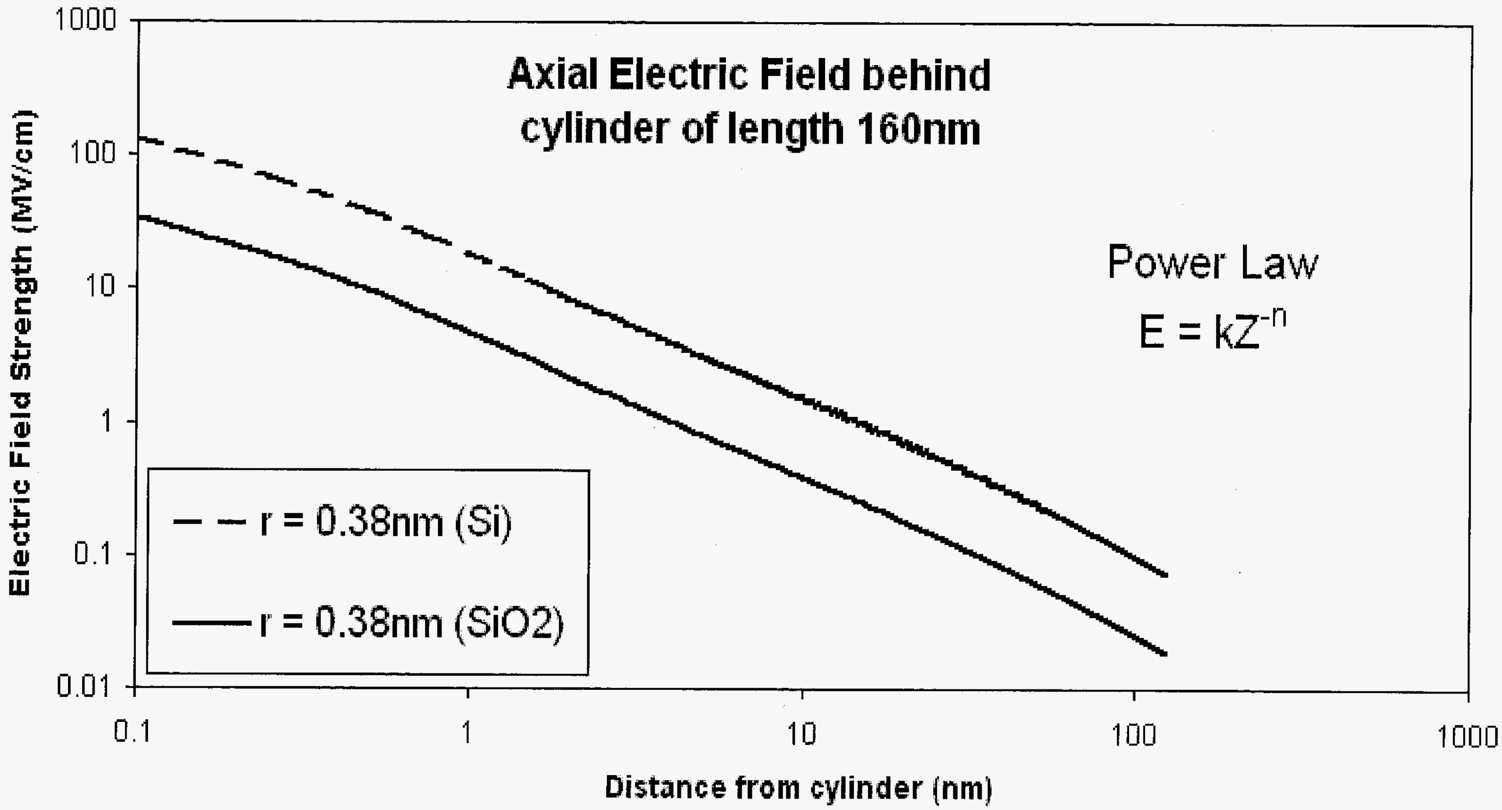
     f(material, doping concentration)

     Range: $1\text{x}10^{-16}$ $1\text{x}10^{-6}$ sec

(M. E. Law, et al. *IEEE Elec. Dev. Let.*, '91)

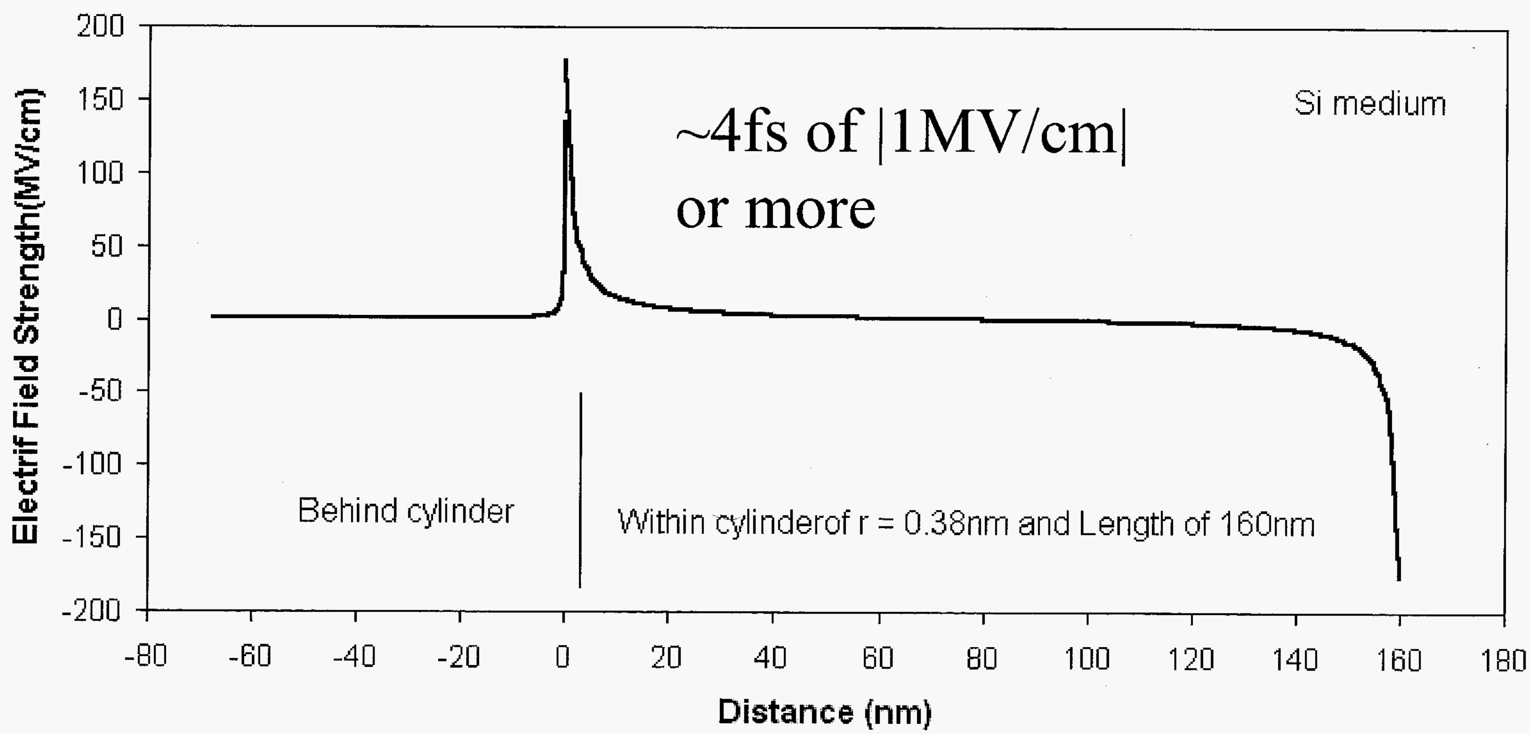
  3) for ß = 0.1 Length = ~150nm

Track-Core (continued)



Track-core (continued)

- Axial Electric Field induced by the ion



Energy Density: Energy Stored

- Ensemble of charges (crystal):

$$w = \frac{1}{2}\sum_{i=1}^{N} q_i \sum_{\substack{j=1 \\ j\neq i}}^{N} \frac{1}{4\pi\varepsilon\varepsilon_0}\frac{q_j}{x_{ij}}$$

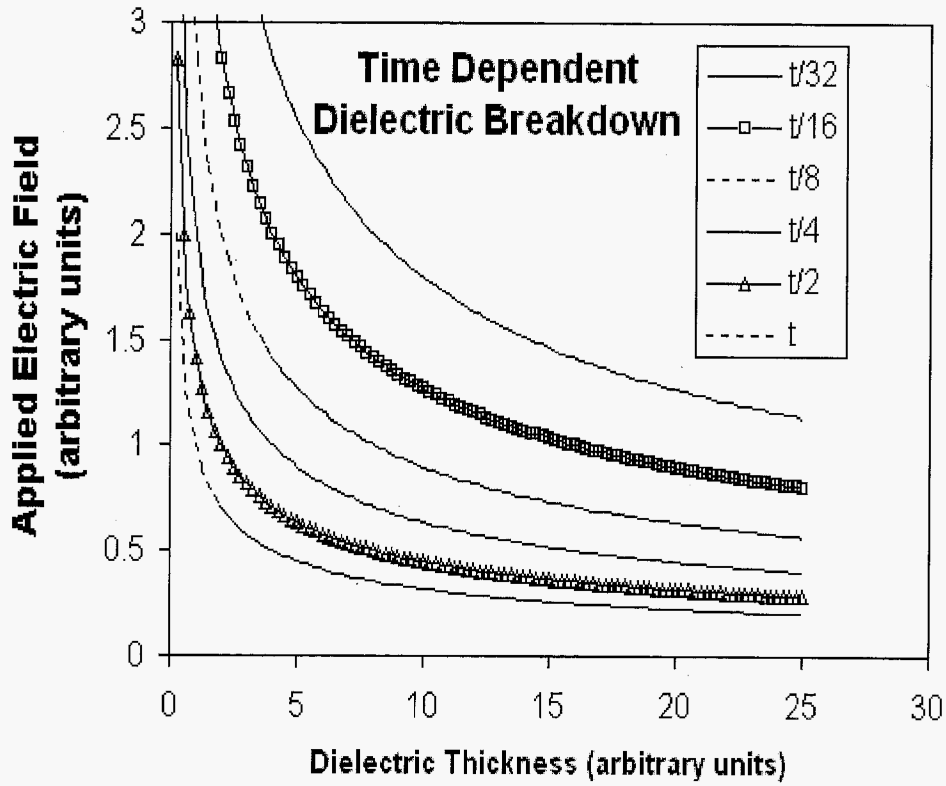
$$w = \frac{\varepsilon\varepsilon_0}{2}\int_{volume} E^2 dV$$

Energy Density: Energy Stored (continued)

- After substitutions

$$E_{crit} = \pm\left[\frac{\hbar}{\varepsilon\varepsilon_0}\frac{1}{A\tau t}\right]^{1/2}$$

- A area
- τ time of impulse
- t thickness



Energy Density: Energy Stored (continued)

- Prediction

Ne at $\beta = 0.1$, radius = 0.38nm

1) not enough to rupture SiO_2 but enough to alter the amorphous structure (>10ev/atom)

2) enough energy to rupture Si (thickness < 160nm) and > enough to alter crystal structure (>25ev/atom)

Energy Density: Energy Stored (continued)

- Angular Dependence:

$$w = \frac{\varepsilon\varepsilon_0}{2}\left[\int_{surface} V\vec{E}\cdot d\vec{a} + \int_{volume} E^2 dV\right]$$

$$w = \frac{1}{k}\left[0 + \int_{volume}\left(\vec{E}_{pre} + \vec{E}_{ind}\right)^2 dV\right]$$

$$k\frac{dw}{dV} = E_{pre}^2 + E_{ind}^2 + 2E_{pre}E_{ind}\cos\theta$$

Energy Density: Energy Stored (continued)

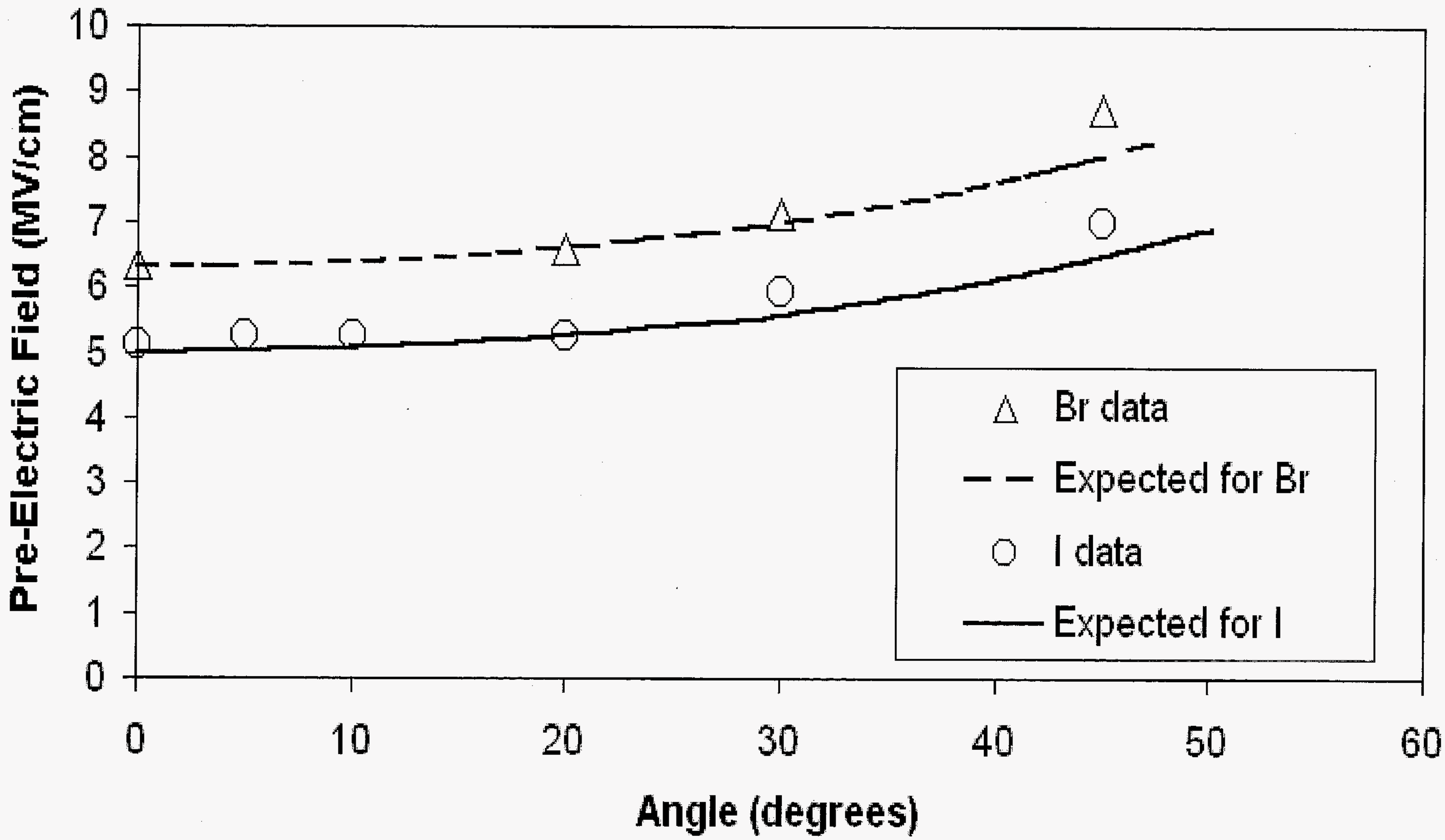
- Solution:

$$E_{pre}(\theta) = -E_{ind}\cos(\theta) \pm \left[E_{ind}^2 \sin^2(\theta) + ED_{crit}\right]^{1/2}$$

- $\theta = 0°$ $E_{pre} = -E_{ind} + [ED_{crit}]^{1/2}$
- $\theta = 180°$ $E_{pre} = E_{ind} - [ED_{crit}]^{1/2}$
- Prediction: Reverse bias = Forward bias
- Experimentally confirmed

Experimental Results: Angular Dependence

- SEGR: IR2N6782 (100V)



Conclusion

A new phenomenological model

1) Ensemble of charges: stored energy

2) Removal of electrons $\Rightarrow$ energy release

3) Energy from induced potential and E.F.s

4) Angular dependence arises from $\mathbf{E}_1 + \mathbf{E}_2$

5) Time dependent dielectric breakdown (TDDB)