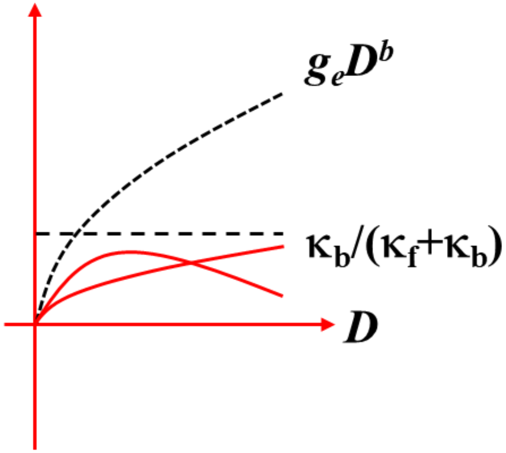
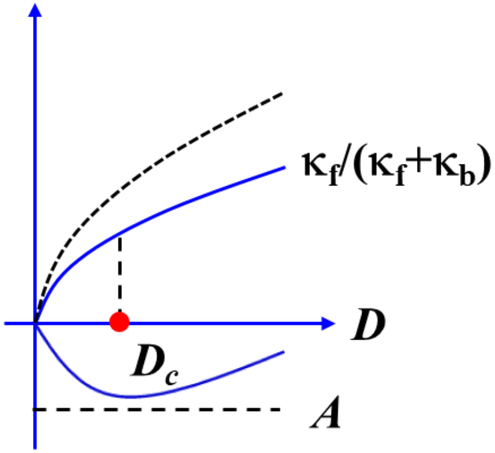
硅基器件的辐照损伤机理

宋 宇

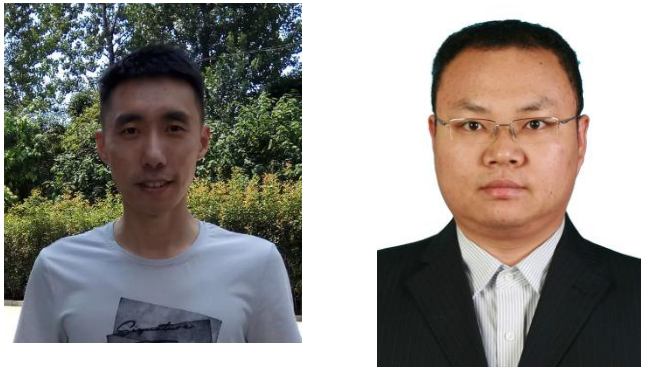
内江师范学院


oxygen vacancies in bulk


dangling bonds at interface

ACKNOWLEDGEMENTS

✓ Prof. Su-Huai Wei, CSRC



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✓ Dr. Hang Zhou, MTRC

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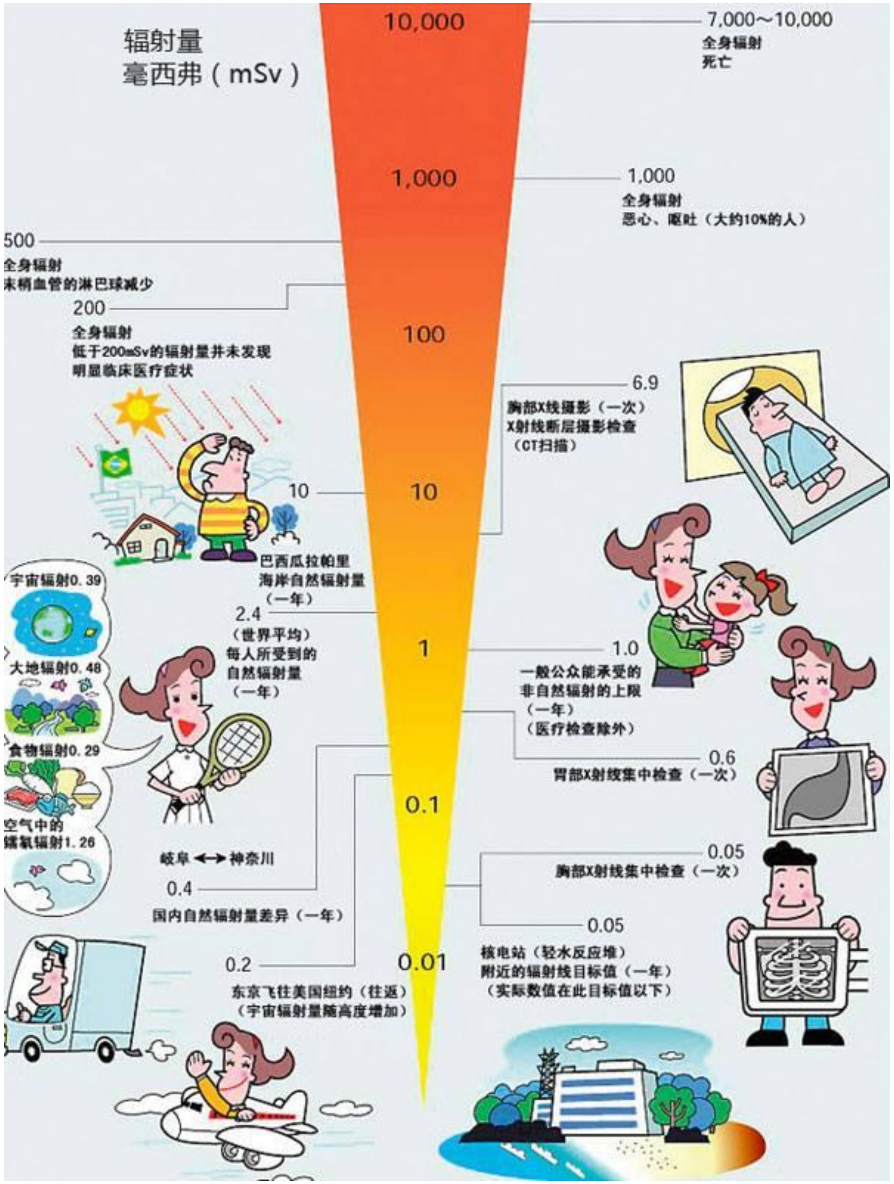
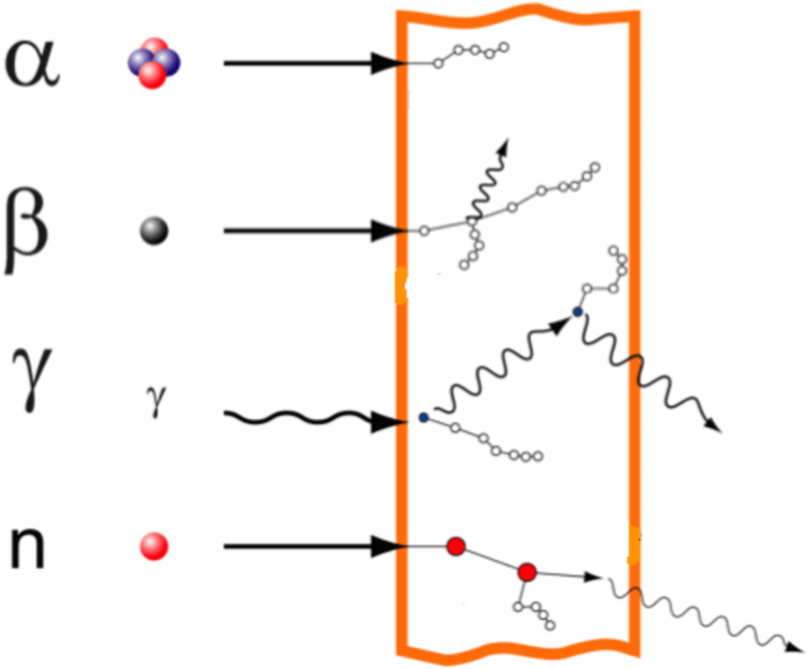
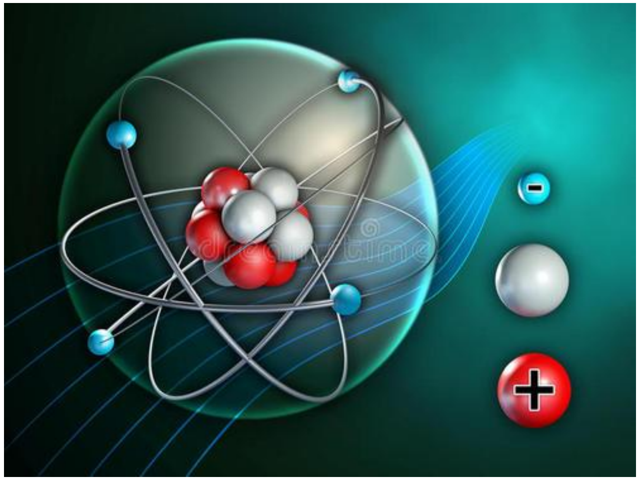
工程价值：国民经济、国家安全



学术价值：强烈的非平衡态物理





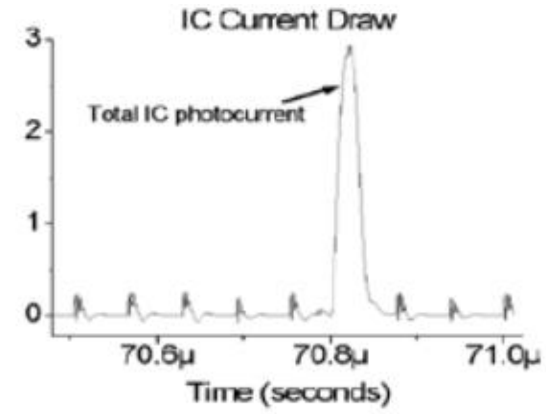
Irradiation defect dynamics: Generation, transport, and reaction of defects in semiconductors

Irradiation (辐照) vs Radiation (辐射)

辐照损伤的基本类型

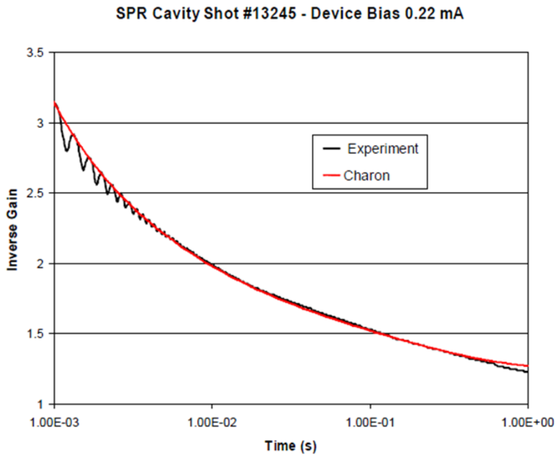
电离能损产生电子空穴对

- **Total ionization dose (TID)**
- Transient photocurrent



非电离能损产生离位原子

- single event effects
- **Displacement damage (DD)**
- Pulsed DD



难以处理的两个极限情况：剂量率特别大、剂量率特别小

报告题纲

Part I: 硅基器件电离损伤的机理

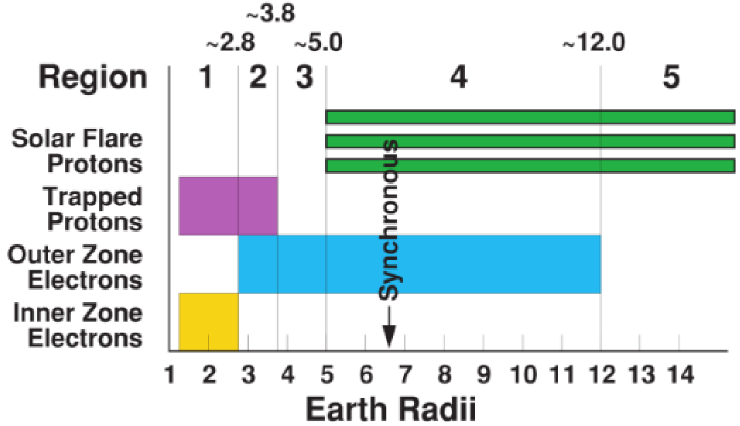
Part II: 硅基器件位移损伤的机理

Part III: 硅基器件位移-电离辐照协同效应的机理

报告题纲

Part I: 硅基器件电离损伤的机理

空间辐射的粒子种类与剂量率水平



- ✓ 高能电子
- ✓ 质子
- ✓ 重离子

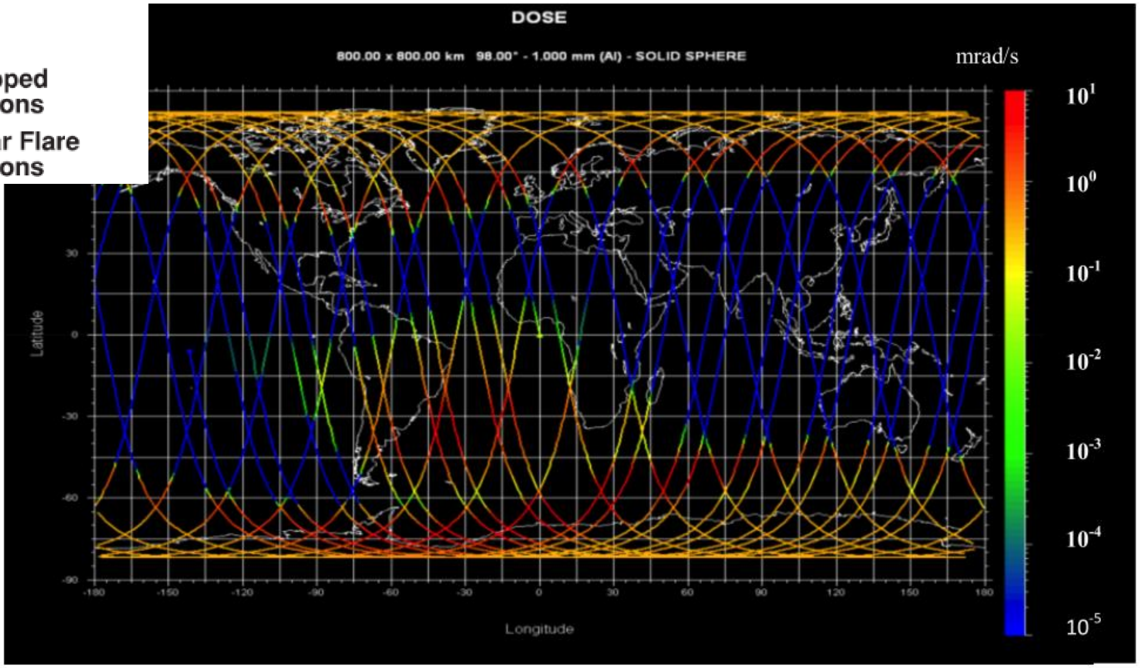
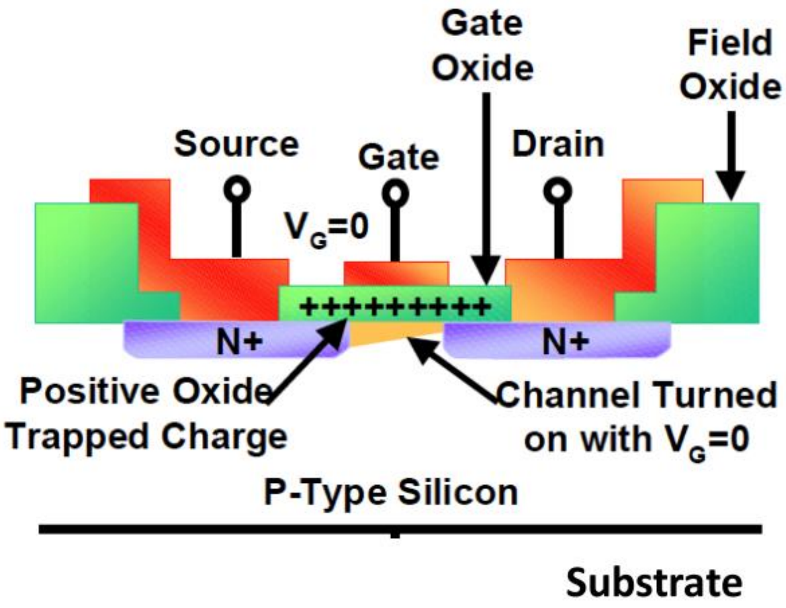


Figure 2. Dose rate along LEO polar orbit (800 km with 98° inclination). From OMERE, a freeware for space radiation environment and effects (TRAD, Tests & Radiations).

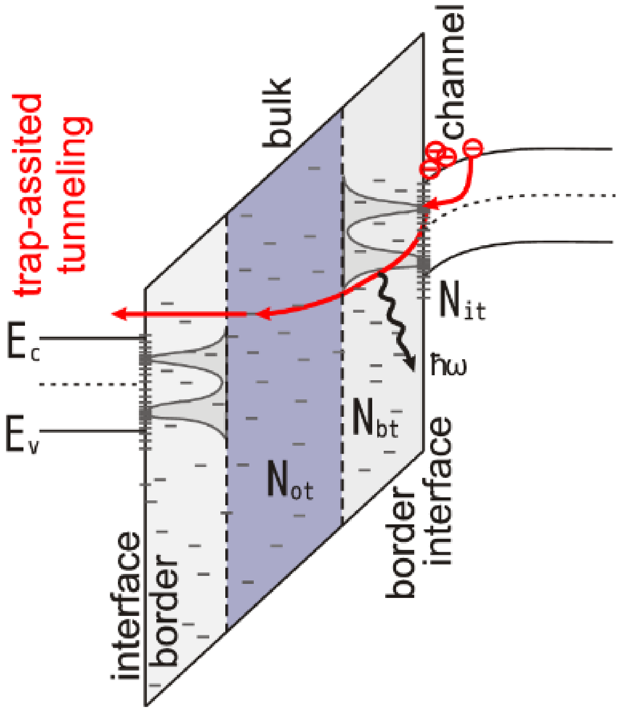
MOSFET中的总剂量(total ionization dose)效应

p-channel MOS

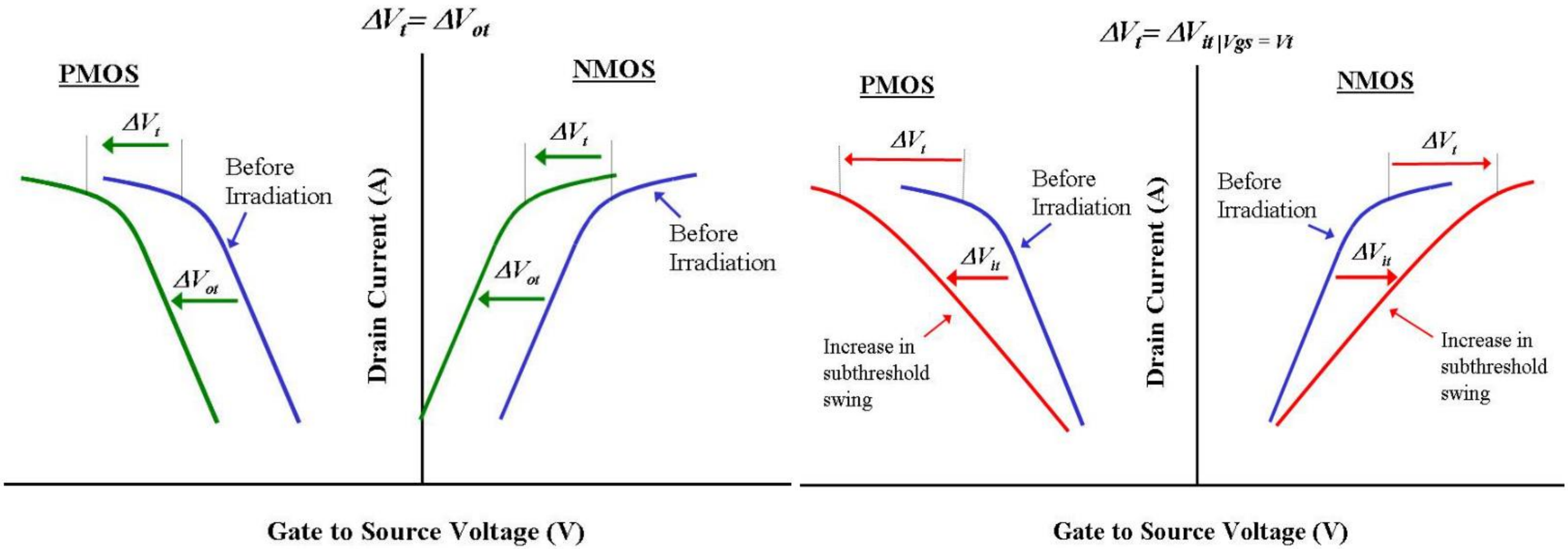


氧化物固定电荷、界面陷阱

Oxide trapped charges & interface traps



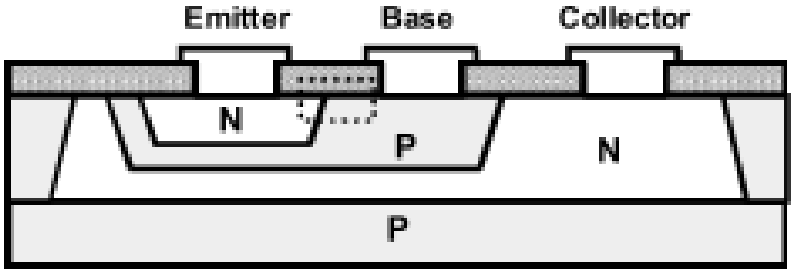
MOSFET中的总剂量(total ionization dose)效应

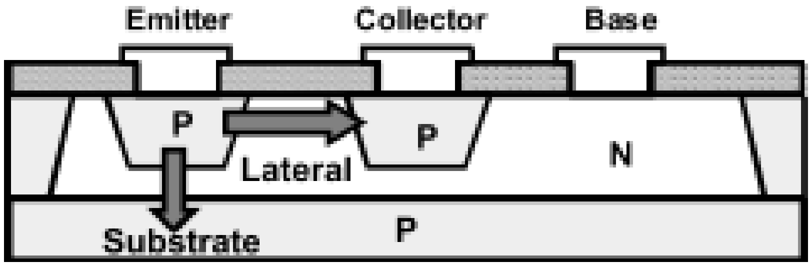


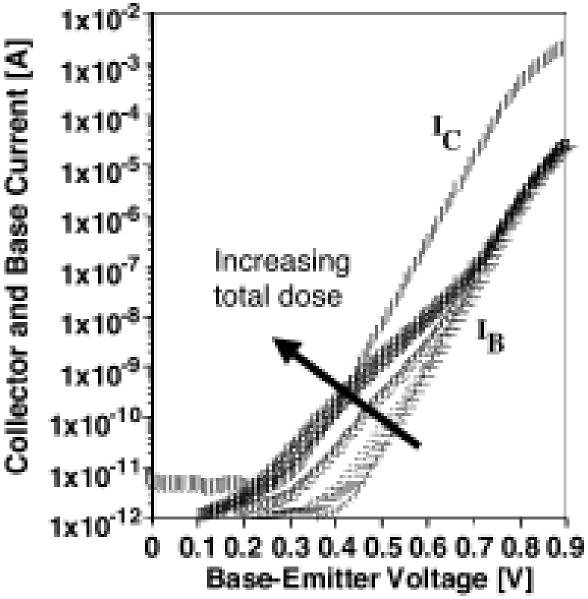
Shift & reshape of I-V characteristics

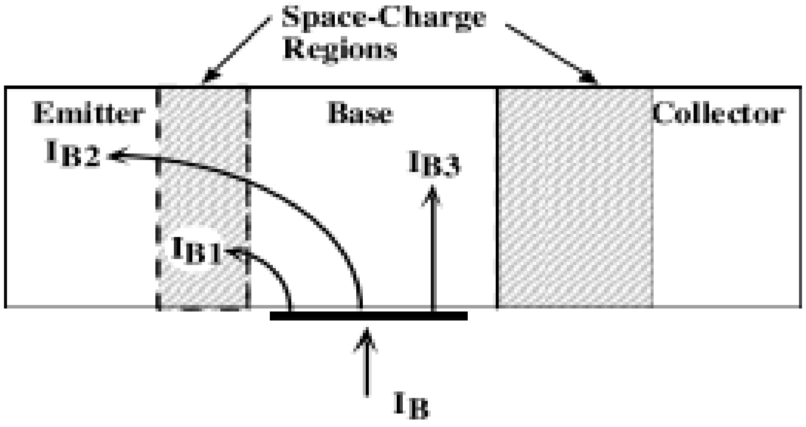
栅极氧化物中电离缺陷的动力学!

BJT中的总剂量效应









$$\Delta I_{\mathrm{R-SCR}}(\psi_s) = \boxed{\Delta s}\,\frac{qP_E V_T \pi n_i}{2E_m \boxed{n_s}} \exp\left(\frac{V_{EB} - I_E R_s}{2V_T}\right)$$

$$\Delta I_{\mathrm{R-NBS}}(\psi_s) = \boxed{\Delta s}\,\frac{qP_E W_B n_i^2}{2\boxed{n_s}(\psi_s)} \left[\exp\left(\frac{V_{EB} - I_E R_s}{V_T}\right) - 1\right]$$

E-B结上氧化物中电离缺陷的动力学！

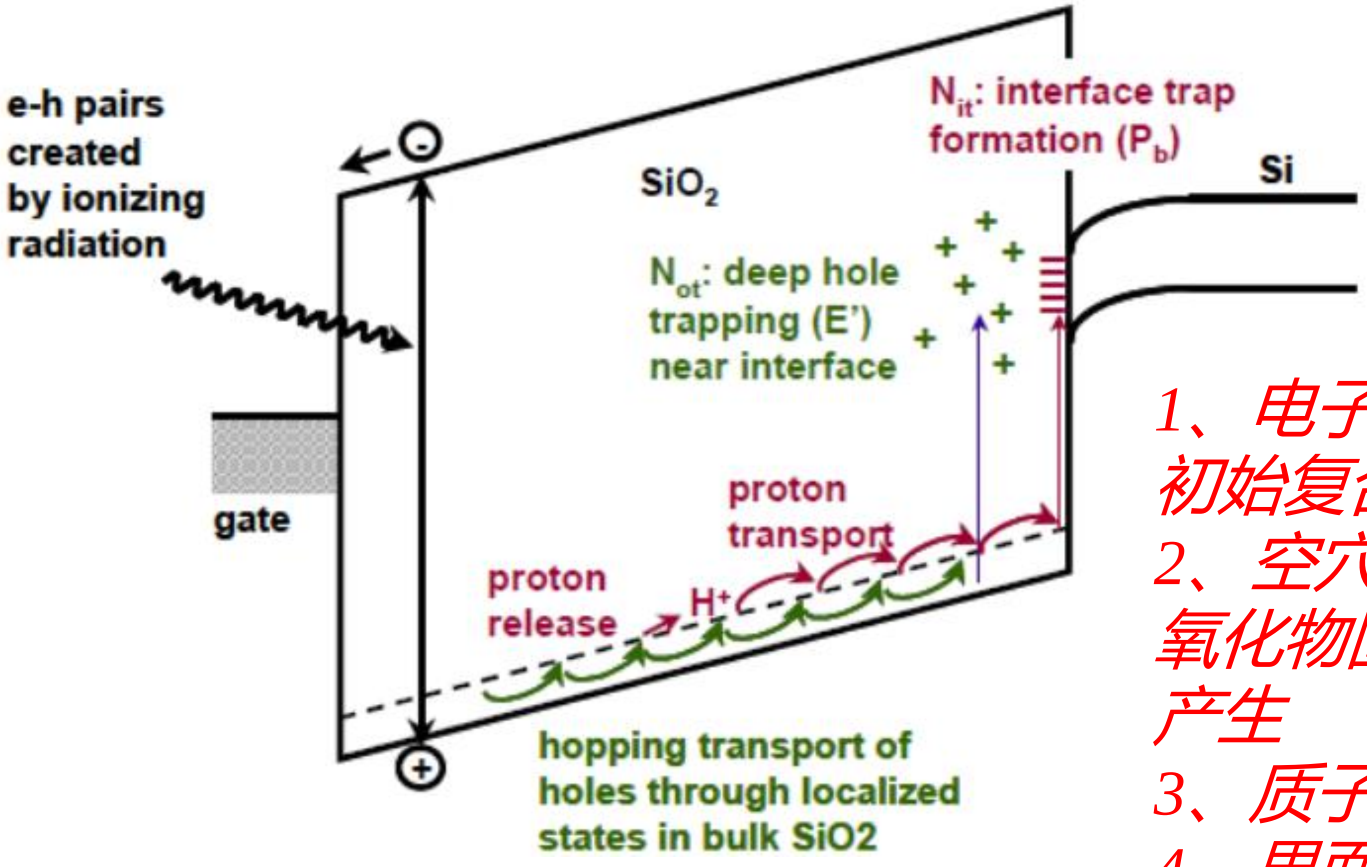
IEEE Trans. Nucl. Sci. 65, 1488 (2018)

Part I 的主要内容

电离缺陷动力学机理

- **学界标准模型**
- 物理困境与计算困难
- 新近发展
- 研究展望

电离缺陷动力学的标准图像：产生—转化

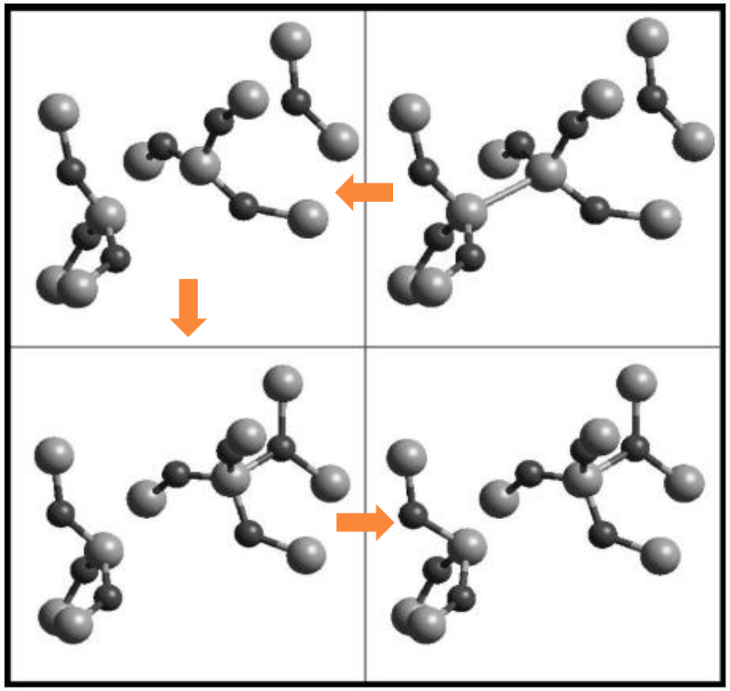


1、电子空穴对的产生与初始复合
2、空穴的输运、俘获与氧化物固定电荷(Not)的产生
3、质子的释放与输运
4、界面陷阱(Nit)的产生

辐射作用下OT的产生及其向IT的转化 $p \rightleftarrows OT \rightleftarrows H^{+} \rightarrow IT$

Tech. Rep. (Sandia National Labs., Albuquerque, NM (United States), 1998).

氧化物固定电荷的结构：氧空位



dimmer

pucker

FIG. 1. Structures of the oxygen vacancy. Top left: [SiSi$^+$] or E'_δ center; top right: [SiSi], the stable configuration of the oxygen vacancy; bottom left: [Si(3)+O(3)$^+$] or E'_γ center; bottom right: [Si(3)$^-$+O(3)$^+$].

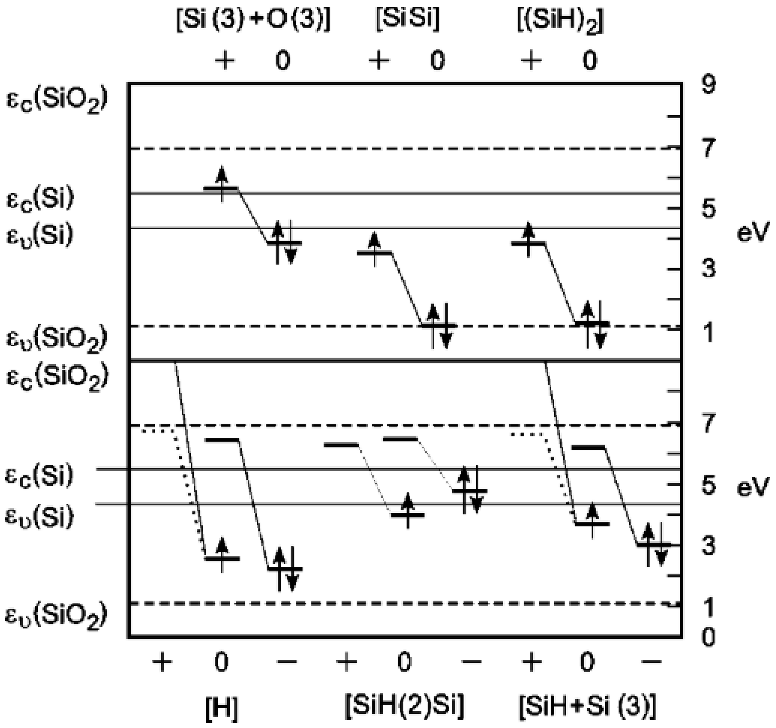


FIG. 2. Switching charge-state levels.

Blöchl, P. E. (2000). ***Physical Review B***, *62*(10), 6158.

氧化物固定电荷的结构：氢化氧空位

二氧化硅中有大量的H，可以与氧空位相互作用形成复合缺陷，性质类似

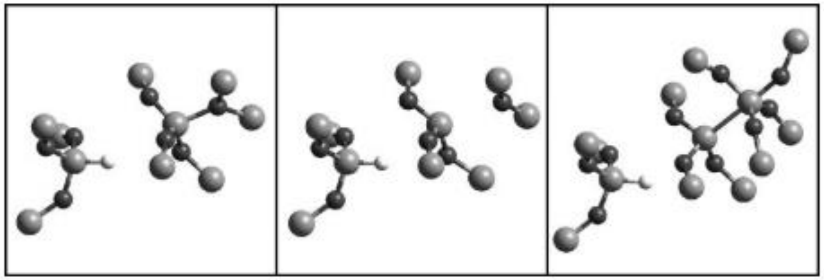


FIG. 9. Structure of the hydrogenated oxygen vacancy in the positive [SiH+O(3)$^+$] (left), the neutral [SiH+Si(3)] (middle), and negative [SiH+SiSi(5)$^-$] (right) charge state.

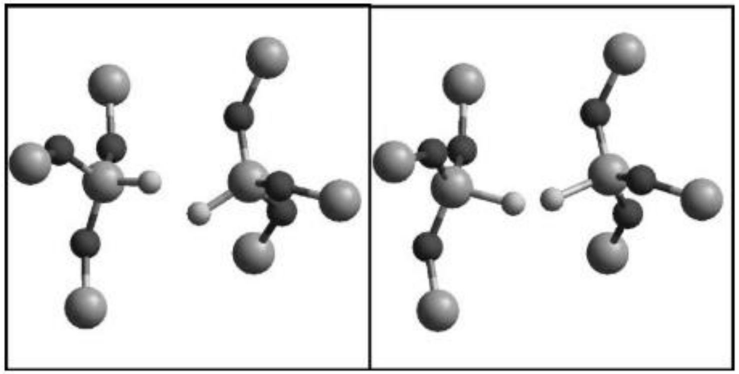


FIG. 10. Structure of the oxygen vacancy interacting with two hydrogen atoms [(SiH)$_2$] in the neutral (left) and positive (right) charge states.

Blöchl, P. E. (2000). ***Physical Review B***, *62*(10), 6158.

氢和质子的微观结构

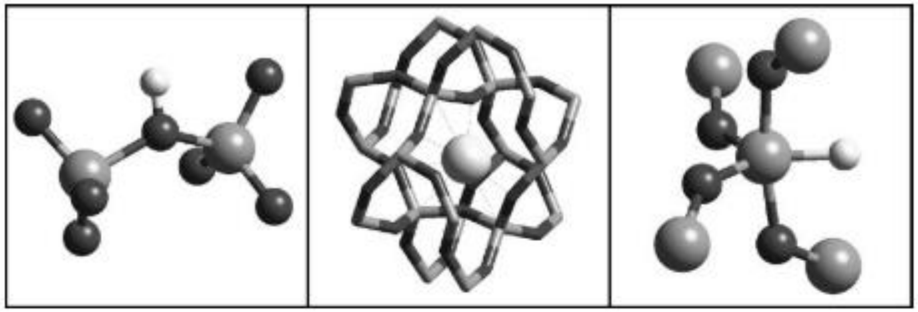
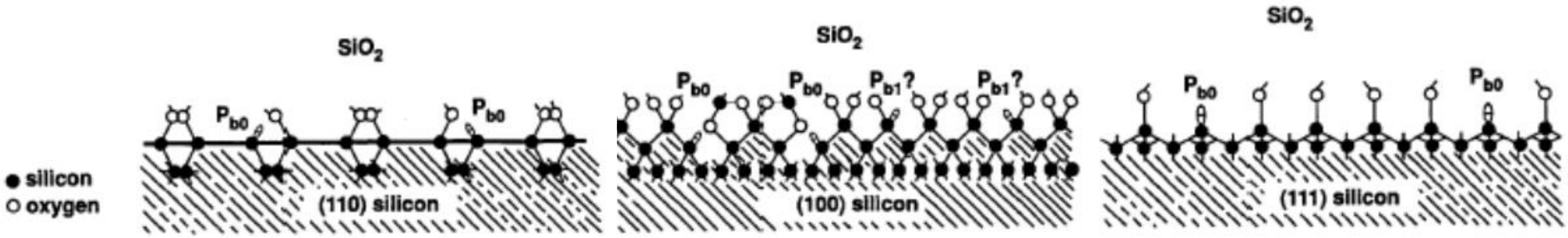


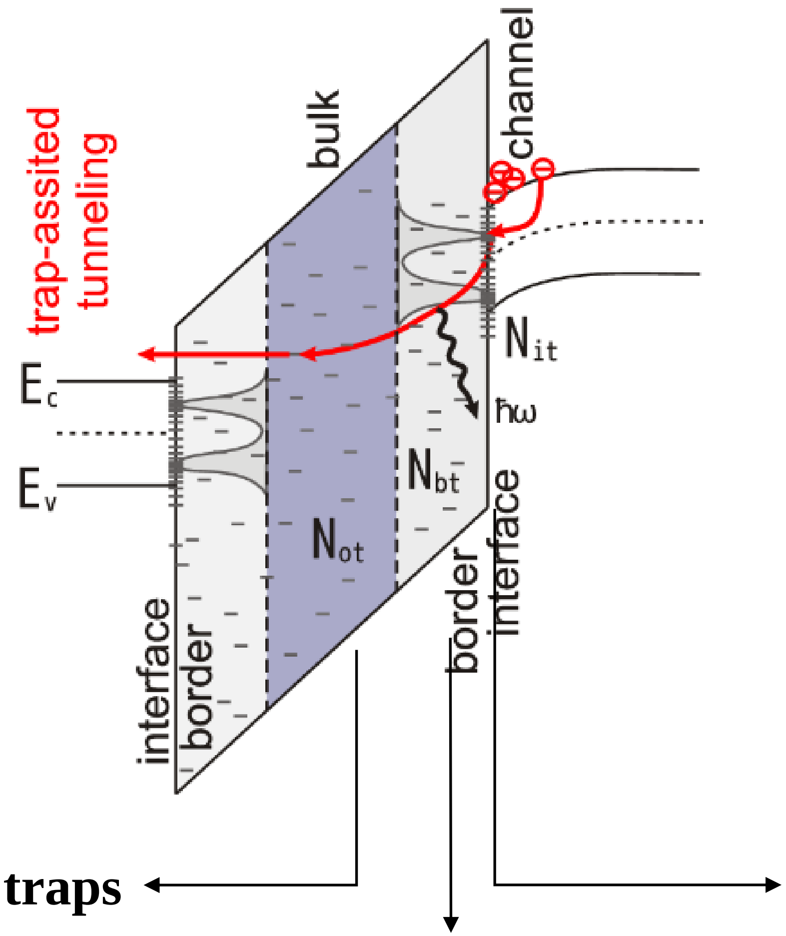
FIG. 5. Structures of the interstitial hydrogen atoms in the positive $[O(3)^{+}H]$, neutral $[H(0)^{0}]$ and negative $[Si(5)^{-}H]$ charge states (from left to right).

界面陷阱的结构：硅悬挂键



Blöchl, P. E. (2000). ***Physical Review B***, *62*(10), 6158.

两类缺陷的空间分布



Oxide traps

Interface traps

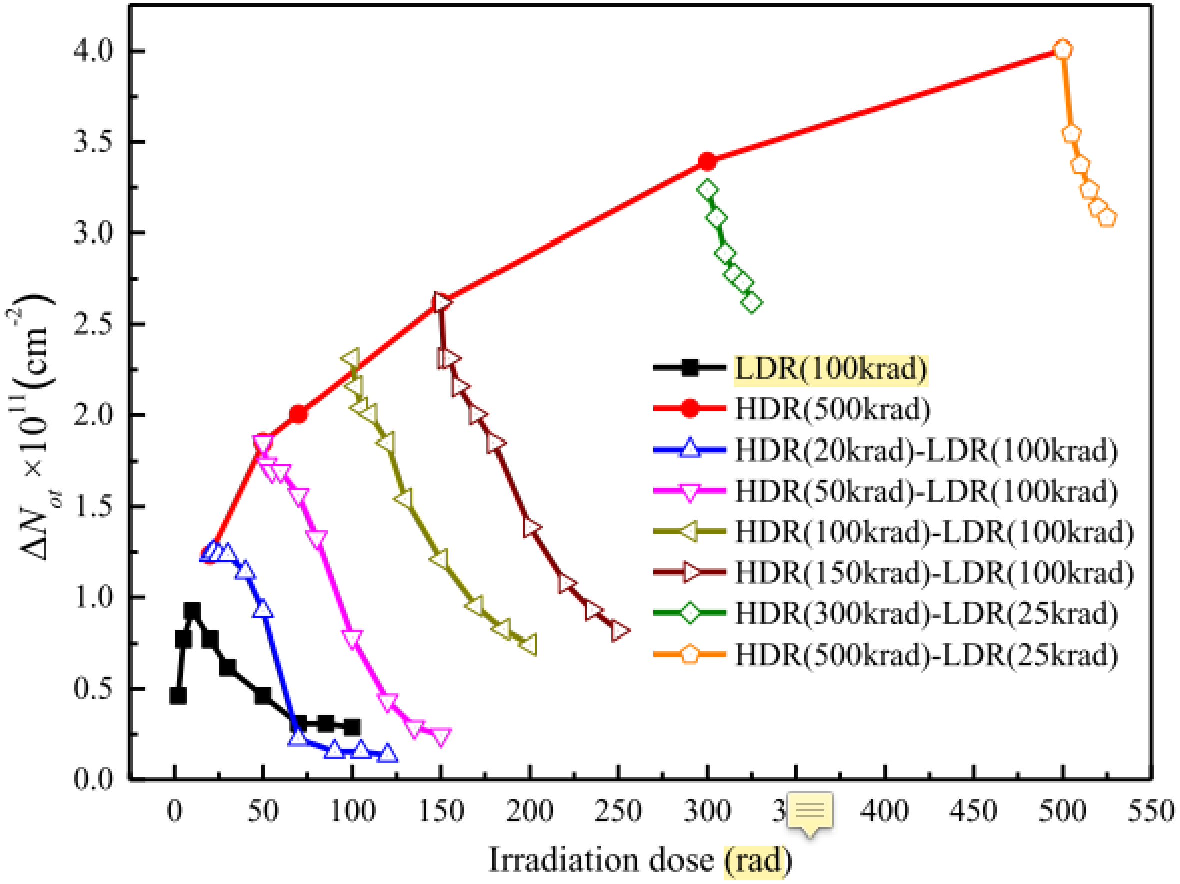
Border traps

Part I 的主要内容

电离缺陷动力学机理

- 学界标准模型
- 物理困境与计算困难
- 新近发展
- 研究展望

物理困境1：难以解释氧空位浓度的剂量依赖

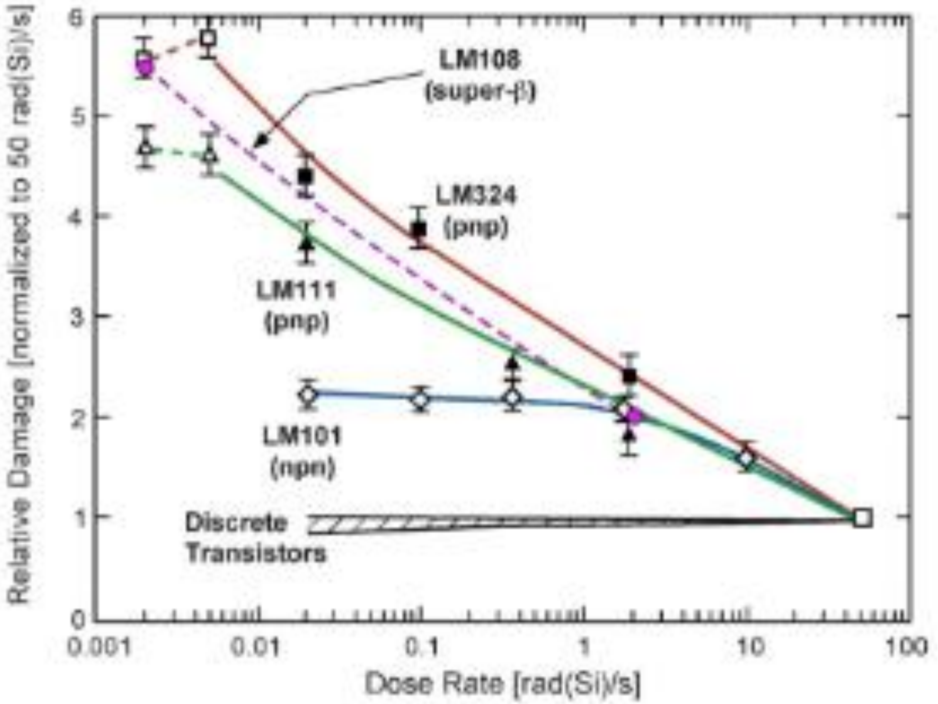


✓ 较低剂量率下，氧空位浓度呈现对辐照电离总剂量的非单调行为

✓ 需要额外的机制：低剂量率下，辐射释放能量，促进ot向it的转化

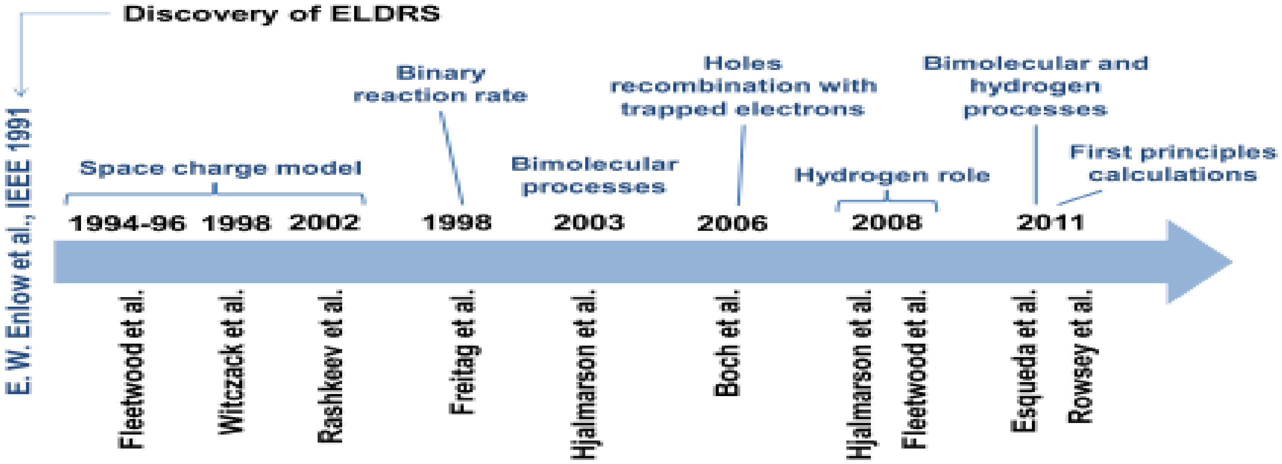
Li, X., ***IEEE Trans. Nucl. Sci.***, 66(7): 1612 (2019).

物理困境2：剂量率依赖的起源众说纷纭



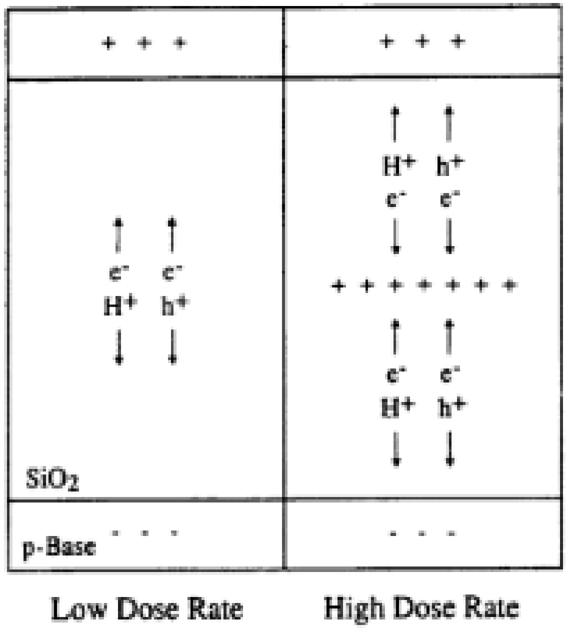
工程：enhanced low-dose-rate sensitivity

物理：reduced high-dose-rate sensitivity

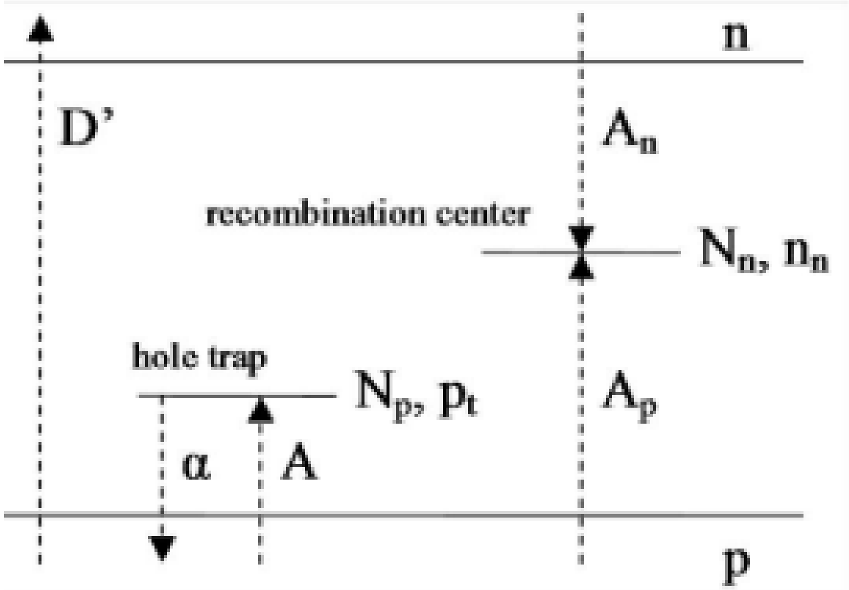


剂量率依赖的代表性模型

空间电荷模型



复合-俘获竞争模型



计算困境：模型复杂性、参数未知性

复杂的耦合微分方程组

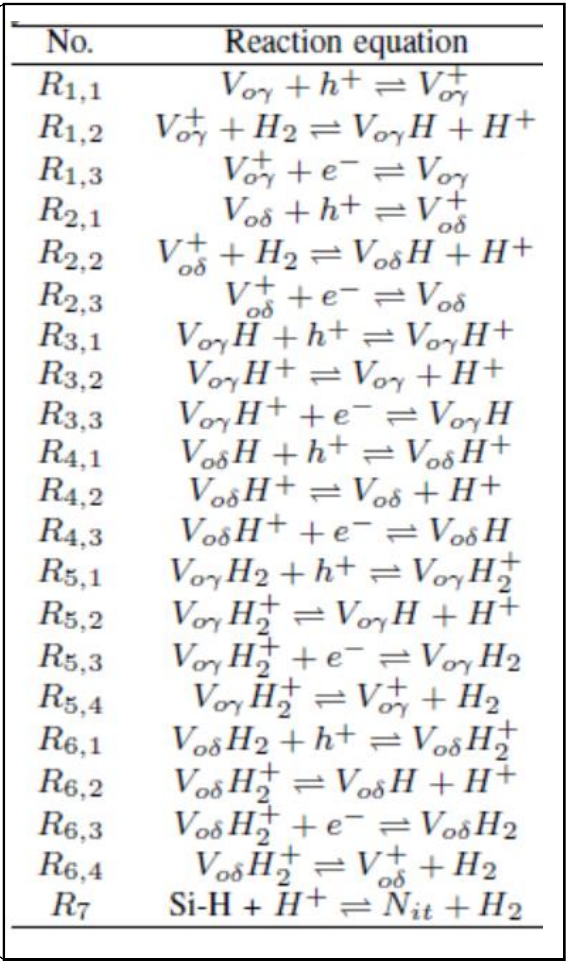
$$\frac{dn}{dt} = \nabla \cdot (\mu_n n\vec{E} + D_n \nabla n) + G_n - R_n$$

$$\frac{dp}{dt} = -\nabla \cdot (\mu_p p\vec{E} - D_p \nabla p) + G_p - R_p$$

$$\boxed{\frac{dT_i}{dt} = G_i - R_i}$$

$$\frac{dH_2}{dt} = \nabla \cdot (D_{H_2} \nabla H_2) + G_{H_2} - R_{H_2}$$

$$\frac{dH^+}{dt} = -\nabla \cdot (\mu_{H^+} H^+ \vec{E} - D_{H^+} \nabla H^+) + G_{H^+} - R_{H^+}$$



No.	Reaction equation
$R_{1,1}$	$V_{o\gamma} + h^+ \rightleftharpoons V_{o\gamma}^+$
$R_{1,2}$	$V_{o\gamma}^+ + H_2 \rightleftharpoons V_{o\gamma}H + H^+$
$R_{1,3}$	$V_{o\gamma}^+ + e^- \rightleftharpoons V_{o\gamma}$
$R_{2,1}$	$V_{o\delta} + h^+ \rightleftharpoons V_{o\delta}^+$
$R_{2,2}$	$V_{o\delta}^+ + H_2 \rightleftharpoons V_{o\delta}H + H^+$
$R_{2,3}$	$V_{o\delta}^+ + e^- \rightleftharpoons V_{o\delta}$
$R_{3,1}$	$V_{o\gamma}H + h^+ \rightleftharpoons V_{o\gamma}H^+$
$R_{3,2}$	$V_{o\gamma}H^+ \rightleftharpoons V_{o\gamma} + H^+$
$R_{3,3}$	$V_{o\gamma}H^+ + e^- \rightleftharpoons V_{o\gamma}H$
$R_{4,1}$	$V_{o\delta}H + h^+ \rightleftharpoons V_{o\delta}H^+$
$R_{4,2}$	$V_{o\delta}H^+ \rightleftharpoons V_{o\delta} + H^+$
$R_{4,3}$	$V_{o\delta}H^+ + e^- \rightleftharpoons V_{o\delta}H$
$R_{5,1}$	$V_{o\gamma}H_2 + h^+ \rightleftharpoons V_{o\gamma}H_2^+$
$R_{5,2}$	$V_{o\gamma}H_2^+ \rightleftharpoons V_{o\gamma}H + H^+$
$R_{5,3}$	$V_{o\gamma}H_2^+ + e^- \rightleftharpoons V_{o\gamma}H_2$
$R_{5,4}$	$V_{o\gamma}H_2^+ \rightleftharpoons V_{o\gamma}^+ + H_2$
$R_{6,1}$	$V_{o\delta}H_2 + h^+ \rightleftharpoons V_{o\delta}H_2^+$
$R_{6,2}$	$V_{o\delta}H_2^+ \rightleftharpoons V_{o\delta}H + H^+$
$R_{6,3}$	$V_{o\delta}H_2^+ + e^- \rightleftharpoons V_{o\delta}H_2$
$R_{6,4}$	$V_{o\delta}H_2^+ \rightleftharpoons V_{o\delta}^+ + H_2$
R_7	Si-H + $H^+ \rightleftharpoons N_{it} + H_2$

- ✓ 工艺相关的初始缺陷浓度难以测试、计算
- ✓ 缺陷反应势垒难以测试、计算

Part I 的主要内容

电离缺陷动力学机理

学界标准模型

物理困境与计算困难

新近发展

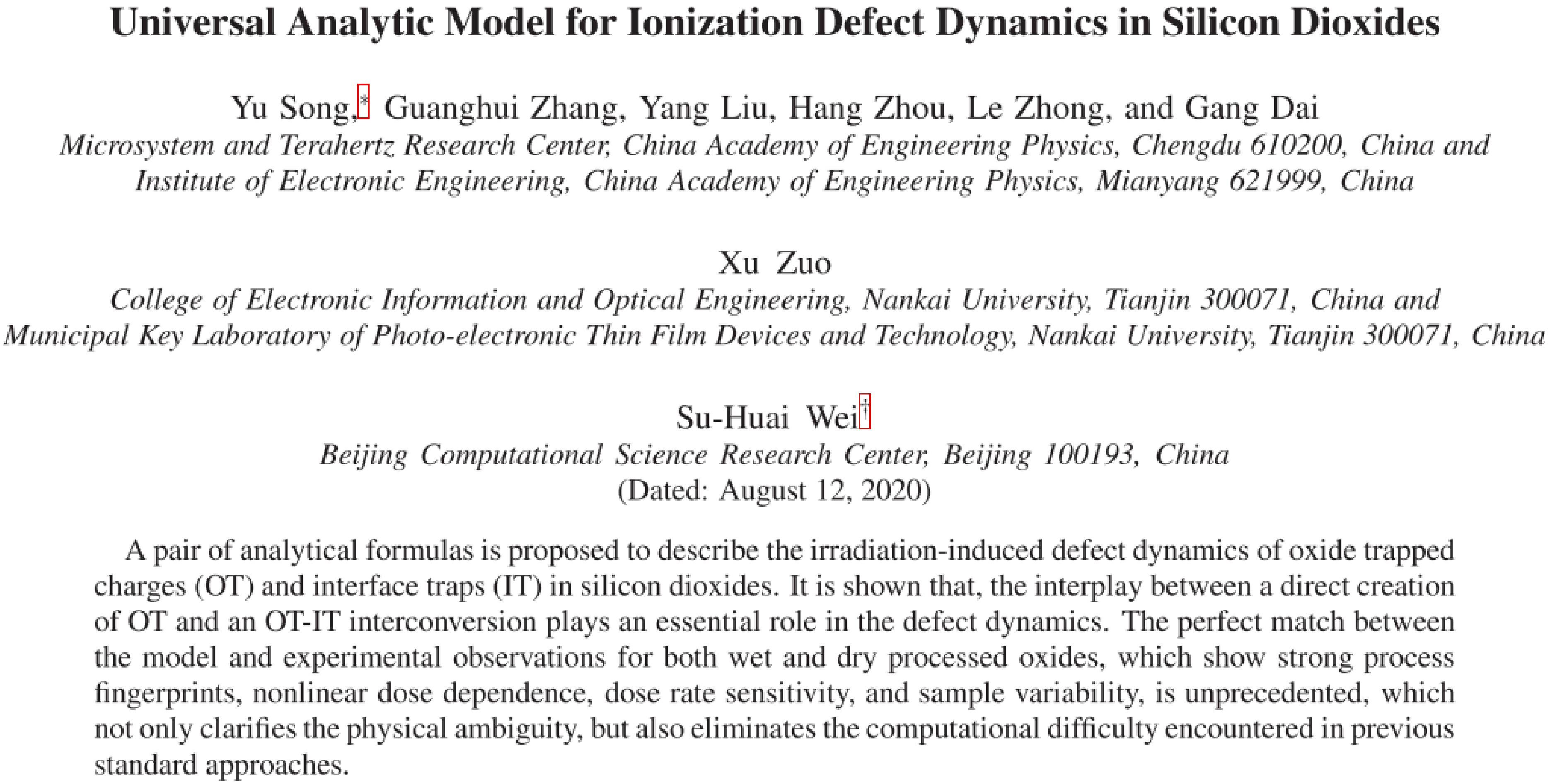
研究展望

电离缺陷动力学的新发展：
*<u>弛豫产生—可逆转化</u>*模型

$$p \underset{k_d}{\overset{k_a}{\rightleftarrows}} OT \boxed{\overset{k_c}{\leftarrow} n} \quad OT \underset{k_{b1}}{\overset{k_{f1}}{\rightleftarrows}} H^+ \underset{\boxed{k_{b2}}}{\overset{k_{f2}}{\rightleftarrows}} IT$$

弛豫过程

$$p \rightleftarrows OT \rightleftarrows H^+ \rightarrow IT$$



Universal Analytic Model for Ionization Defect Dynamics in Silicon Dioxides

Yu Song,[*] Guanghui Zhang, Yang Liu, Hang Zhou, Le Zhong, and Gang Dai
Microsystem and Terahertz Research Center, China Academy of Engineering Physics, Chengdu 610200, China and
Institute of Electronic Engineering, China Academy of Engineering Physics, Mianyang 621999, China

Xu Zuo
College of Electronic Information and Optical Engineering, Nankai University, Tianjin 300071, China and
Municipal Key Laboratory of Photo-electronic Thin Film Devices and Technology, Nankai University, Tianjin 300071, China

Su-Huai Wei[†]
Beijing Computational Science Research Center, Beijing 100193, China

(Dated: August 12, 2020)

A pair of analytical formulas is proposed to describe the irradiation-induced defect dynamics of oxide trapped charges (OT) and interface traps (IT) in silicon dioxides. It is shown that, the interplay between a direct creation of OT and an OT-IT interconversion plays an essential role in the defect dynamics. The perfect match between the model and experimental observations for both wet and dry processed oxides, which show strong process fingerprints, nonlinear dose dependence, dose rate sensitivity, and sample variability, is unprecedented, which not only clarifies the physical ambiguity, but also eliminates the computational difficulty encountered in previous standard approaches.

arXiv:2008.04486

解析模型及其物理意义

3、耦合求解

$$p \underset{k_d}{\overset{k_a}{\rightleftarrows}} OT \overset{k_c}{\leftarrow} n \quad OT \underset{k_{b1}}{\overset{k_{f1}}{\rightleftarrows}} H^+ \underset{k_{b2}}{\overset{k_{f2}}{\rightleftarrows}} IT$$

Compact analytical model with 4 effective parameters

$$V_O(D) = (1-\lambda)g_e D^b + \lambda g_e D_c^b b e^{-\frac{D}{D_c}} \Gamma[b,0,D/D_c],$$

$$P_b(D) = \lambda g_e D^b - \lambda g_e D_c^b b e^{-\frac{D}{D_c}} \Gamma[b,0,D/D_c].$$

产生弛豫因子：b 有效产生速率：$g_e = (N_c + N_a)k^b$

转化比例因子：$\lambda = \kappa_f/(\kappa_f + \kappa_b)$ 特征转化剂量： $D_c = q(\kappa_f + \kappa_b)^{-1}$

Too complex to understand!

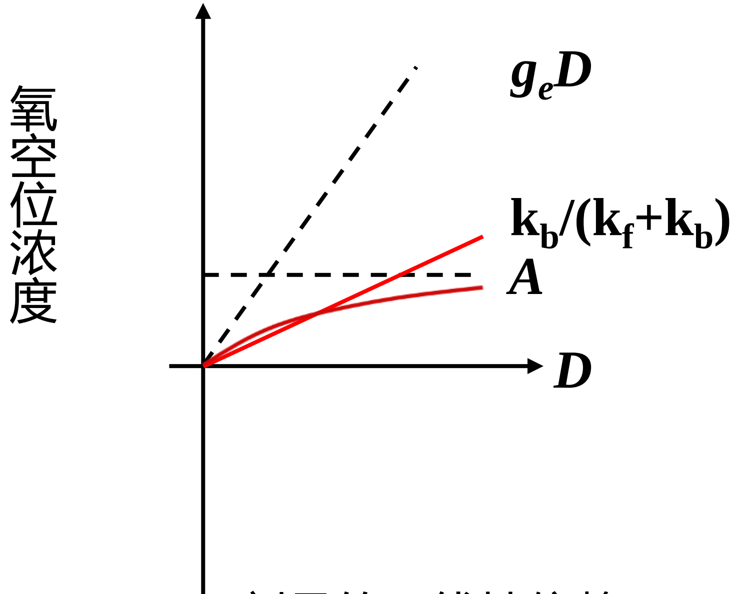
物理意义（b=1的情况）

$$p \underset{k_d}{\overset{k_a}{\rightleftarrows}} OT \overset{k_c}{\leftarrow} n \quad OT \underset{\kappa_b}{\overset{\kappa_f}{\rightleftarrows}} IT$$

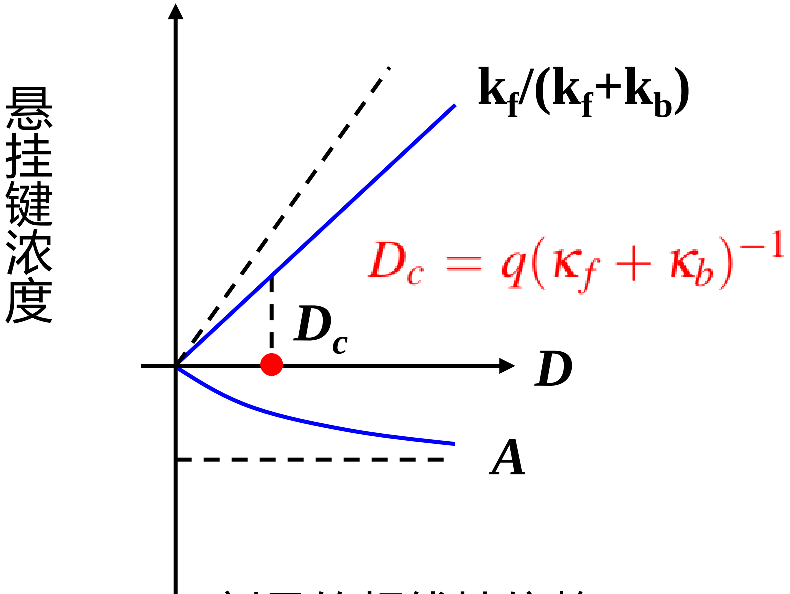
缺陷的正向转化（比重-速率）　　缺陷的逆向转化（强度-产生）

$$V_O(D) = (1-\lambda)g_e D + \lambda g_e D_c[1-e^{-D/D_c}],$$

$$P_b(D) = \lambda g_e D - \lambda g_e D_c[1-e^{-D/D_c}].$$



剂量的亚线性依赖



剂量的超线性依赖

物理意义（b<1的情况）

$$p \underset{k_d}{\overset{k_a}{\rightleftarrows}} OT \overset{k_c}{\leftarrow} n \quad OT \underset{\kappa_b}{\overset{\kappa_f}{\rightleftarrows}} IT$$

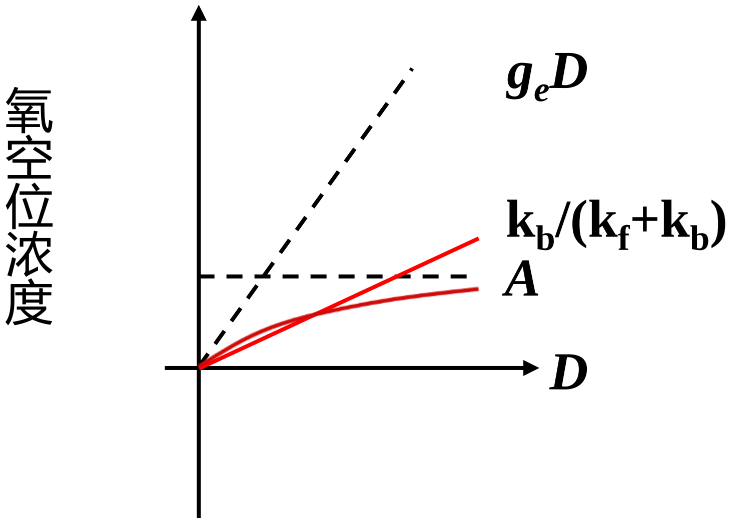
$$V_O(D) = (1-\lambda)g_e D + \lambda g_e D_c[1-e^{-D/D_c}],$$

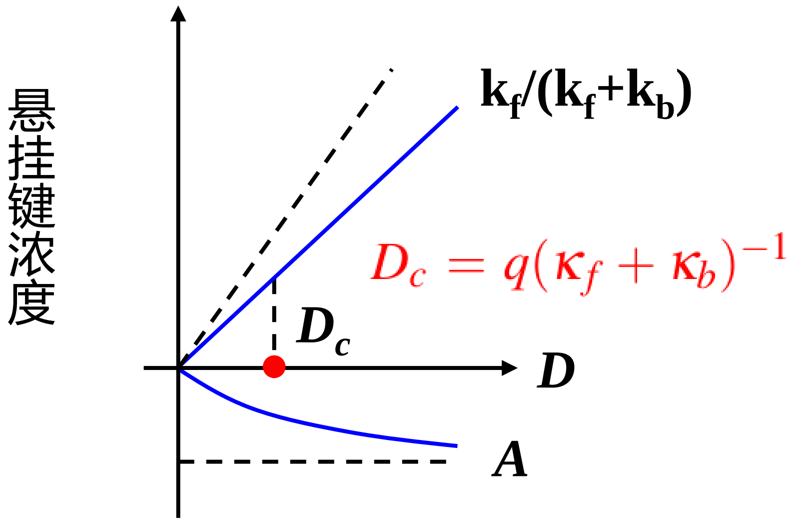
$$P_b(D) = \lambda g_e \boxed{D} - \lambda g_e D_c \boxed{[1-e^{-D/D_c}]}.$$

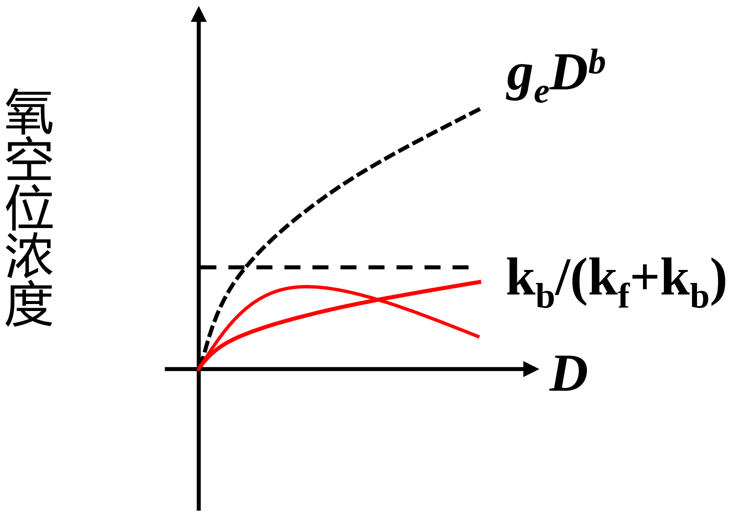
$$V_O(D) = (1-\lambda)g_e \boxed{D^b} + \lambda g_e D_c^b \boxed{b e^{-\frac{D}{D_c}} \Gamma[b,0,D/D_c]},$$

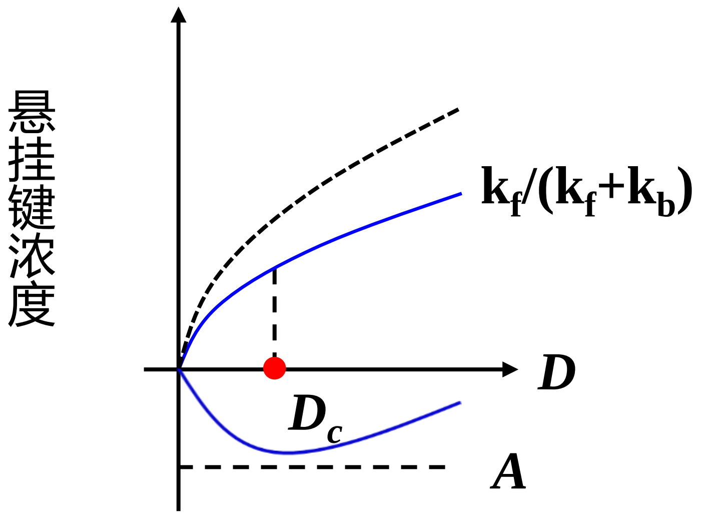
$$P_b(D) = \lambda g_e D^b - \lambda g_e D_c^b b e^{-\frac{D}{D_c}} \Gamma[b,0,D/D_c].$$

物理意义（b<1的情况）





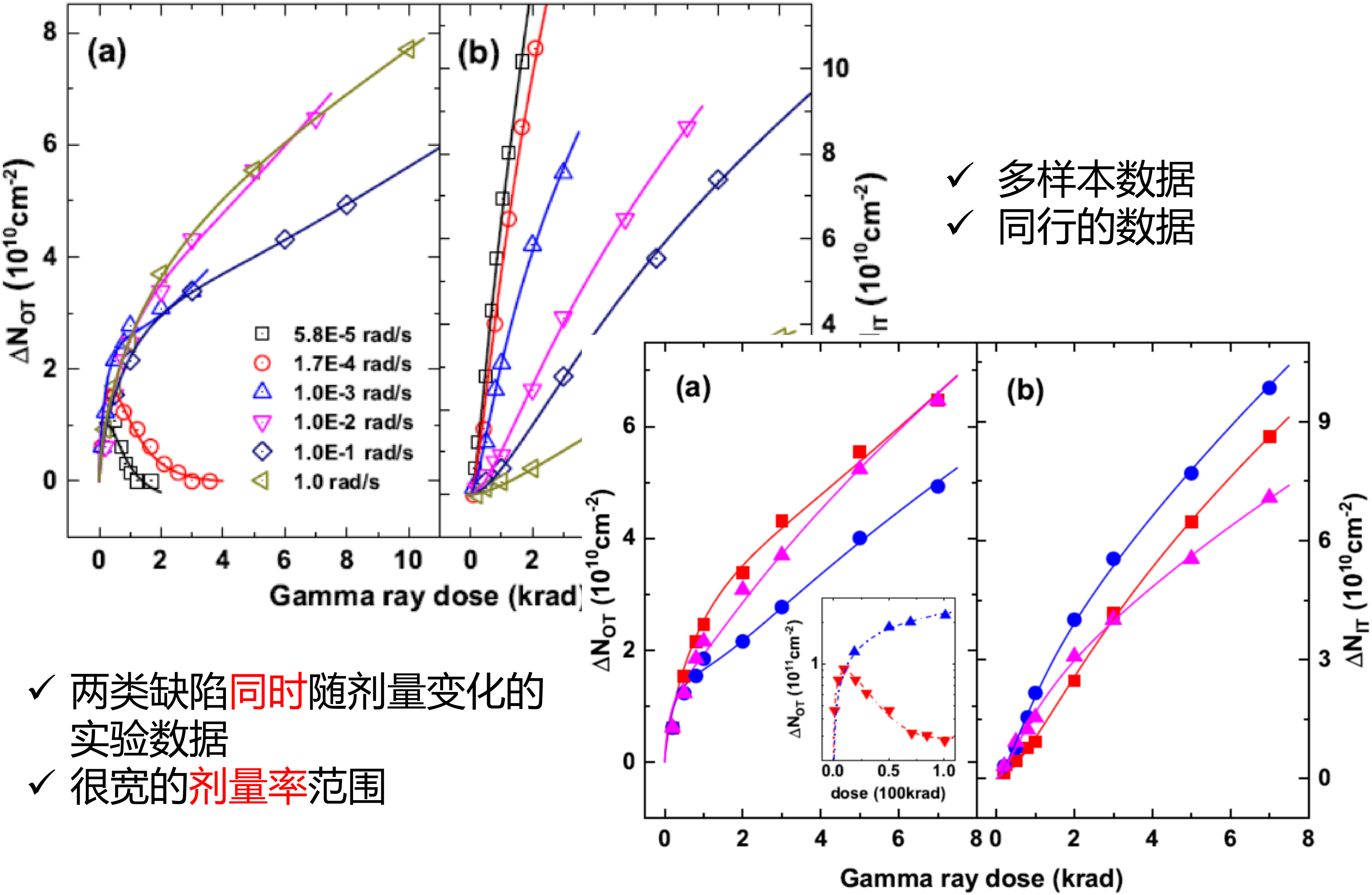




更强的亚线性依赖

更弱的超线性依赖

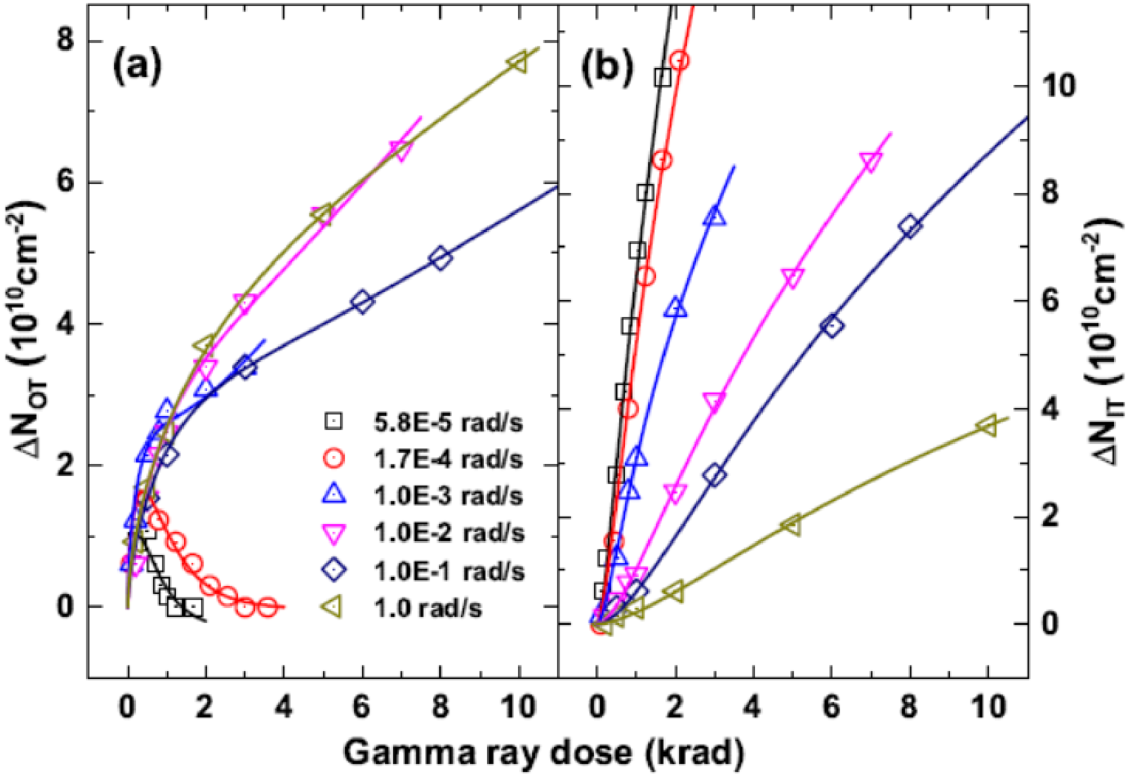
模型(机理)的实验验证

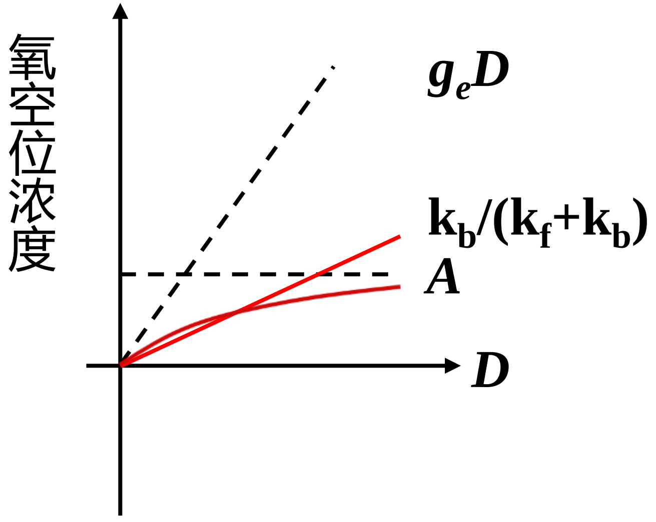


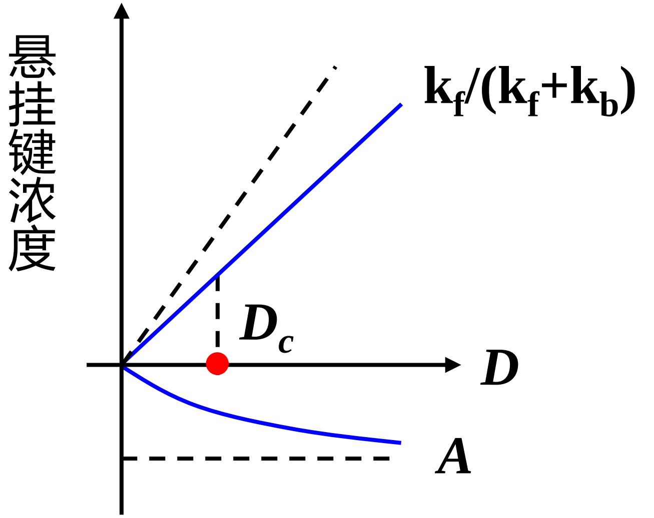
- ✓ 多样本数据
- ✓ 同行的数据

- ✓ 两类缺陷同时随剂量变化的实验数据
- ✓ 很宽的剂量率范围

剂量依赖的物理起源

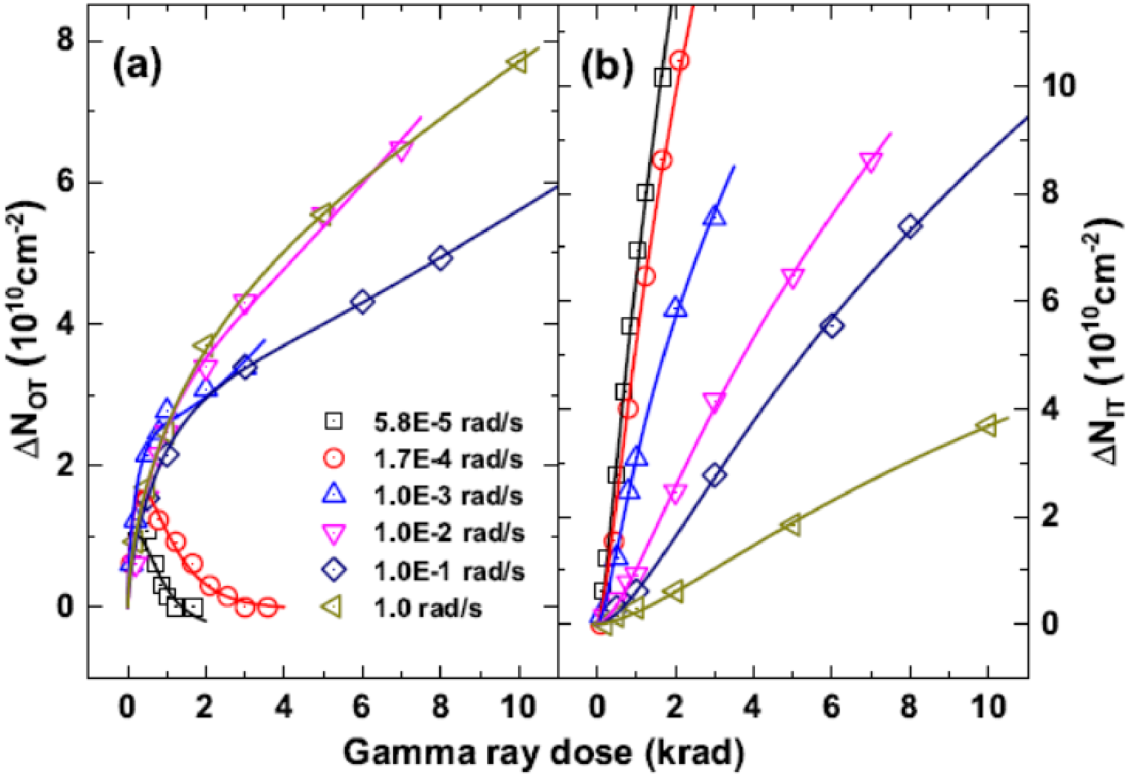


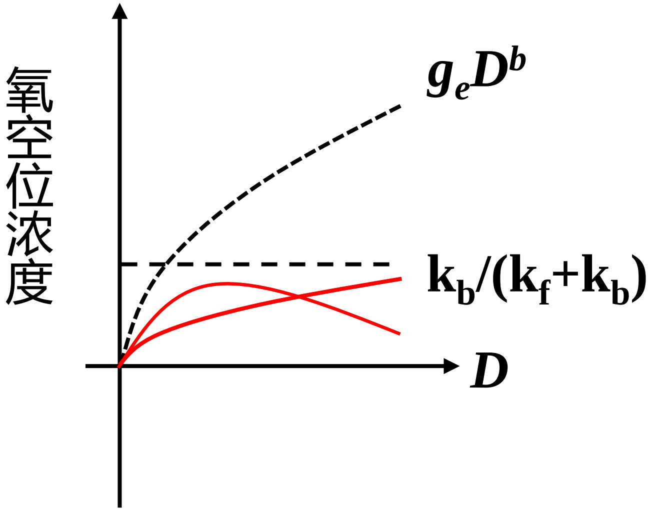


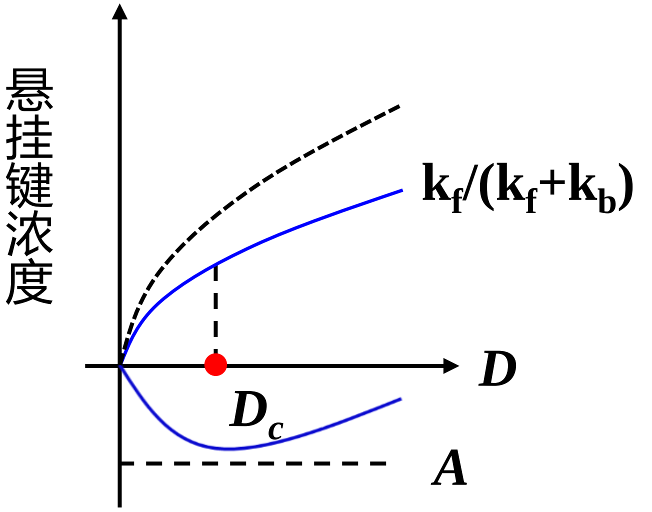


✓氧空位的亚线性和悬挂键的超线性依赖起源于缺陷的相互转化

剂量依赖的物理起源

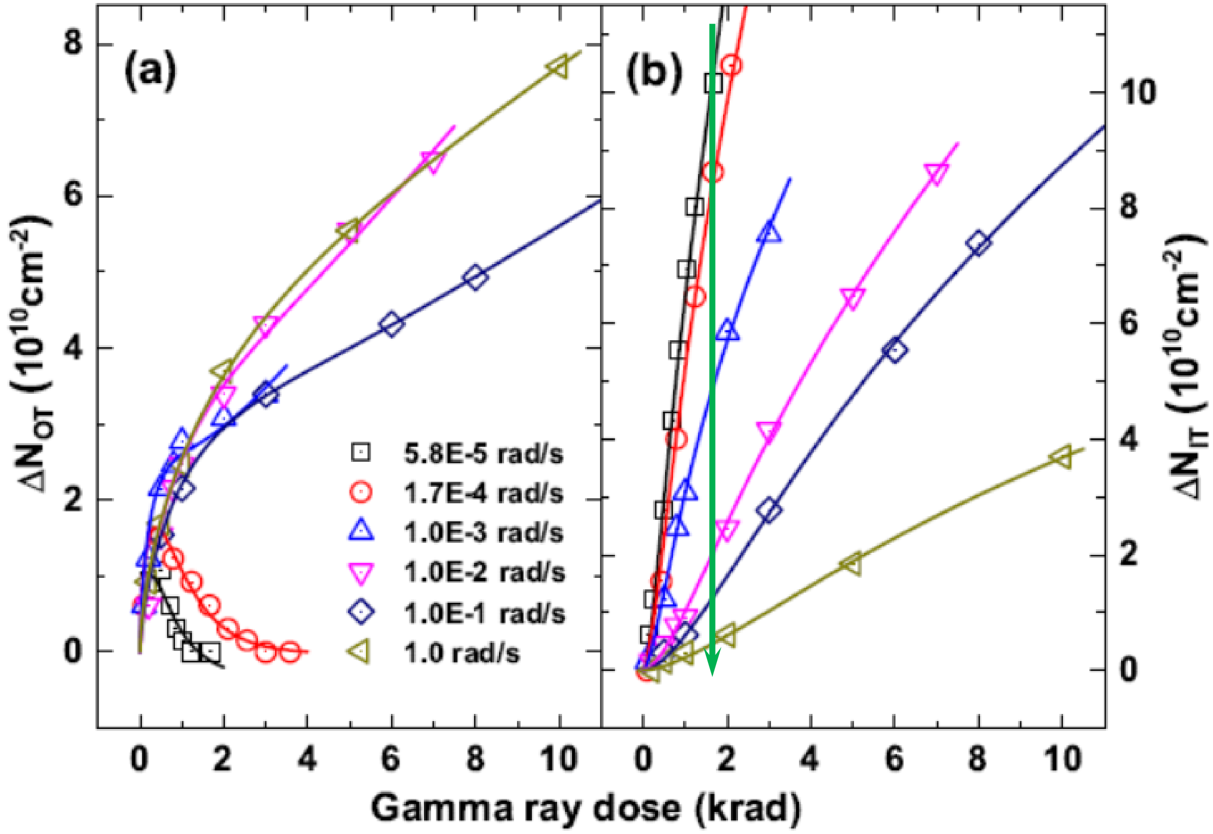






✓浓度和的亚线性(分数幂定律)、氧空位的非单调性起源于缺陷产生的弛豫性

缺陷浓度剂量率依赖的物理起源

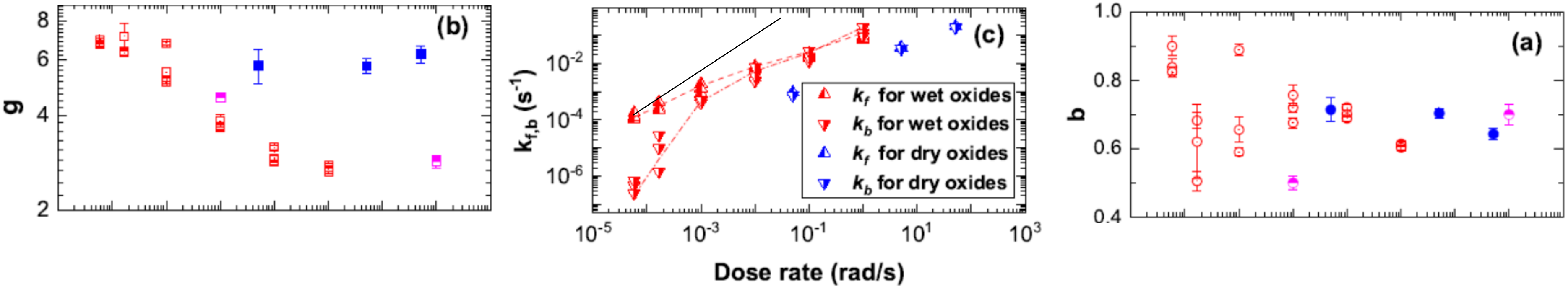


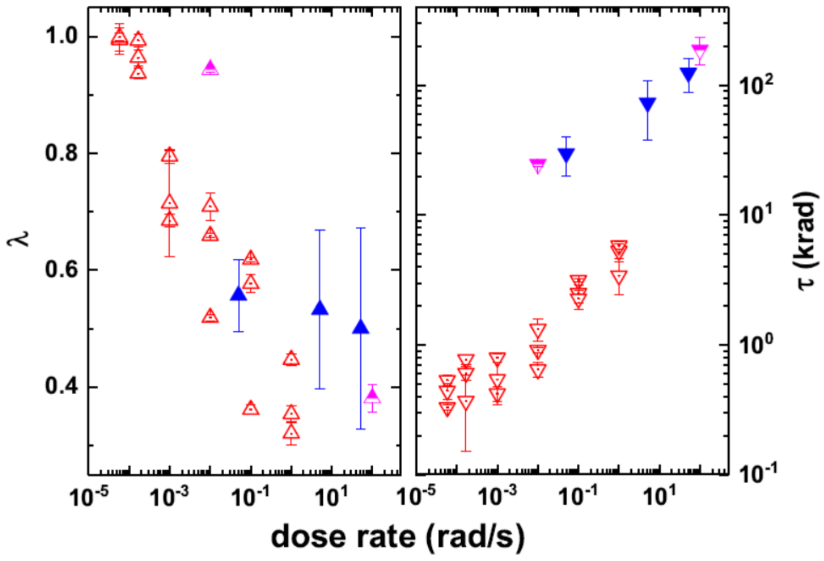
- ✓ 同样的总剂量下，剂量率越高，硅悬挂键越少
- ✓ 工程上无法直接加速试验的原因

缺陷浓度剂量率依赖的物理起源

$$P_b(D) = \lambda g_e D^b - \lambda g_e D_c^b b e^{-\frac{D}{D_c}} \Gamma[b,0,D/D_c].$$

拟合抽取模型参数





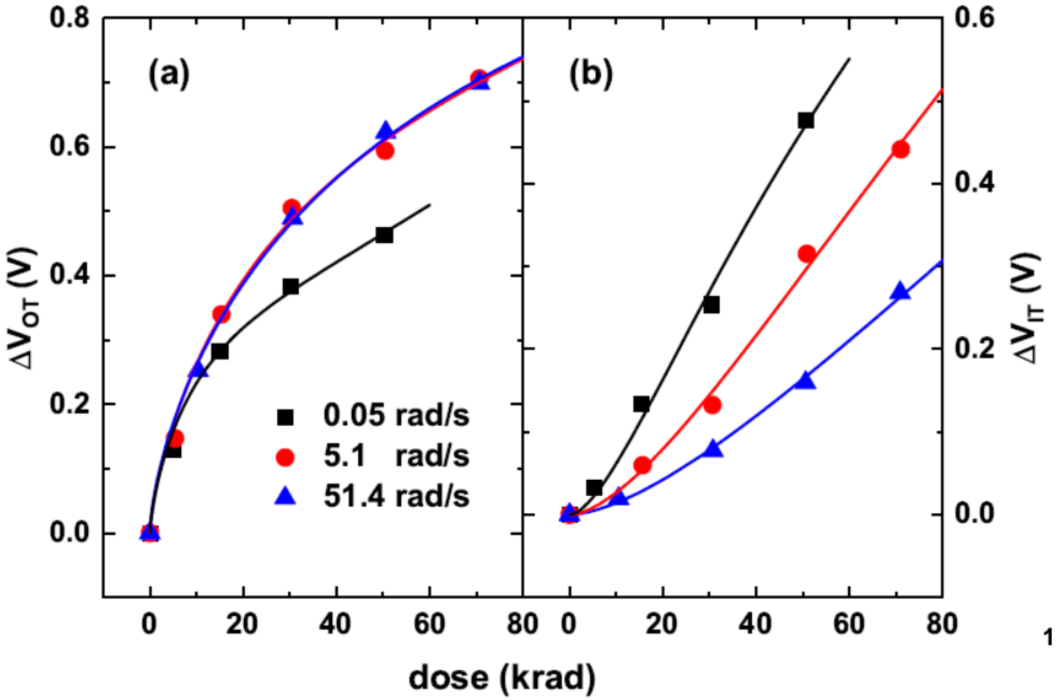
随着剂量率增大

- g_e 降低：逆向产生比重增大
- λ 减小：逆向转化比重增大
- D_c增大：转化速率亚线性增长

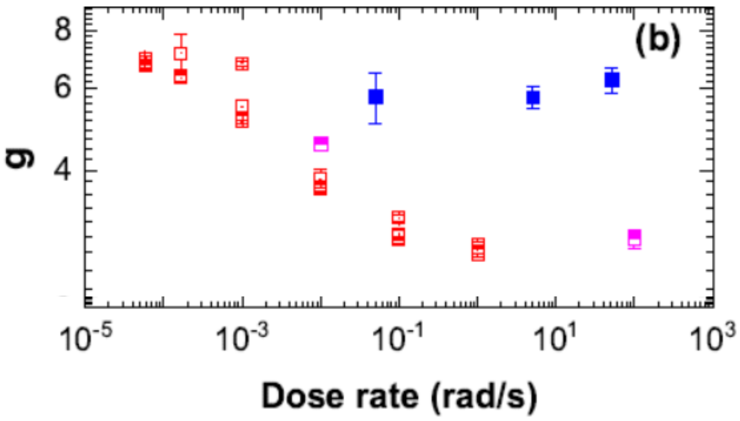
$$p \underset{\boxed{k_d}}{\overset{k_a}{\rightleftharpoons}} OT \xleftarrow{k_c} n \qquad OT \underset{\boxed{\kappa_b}}{\overset{\kappa_f}{\rightleftharpoons}} IT$$

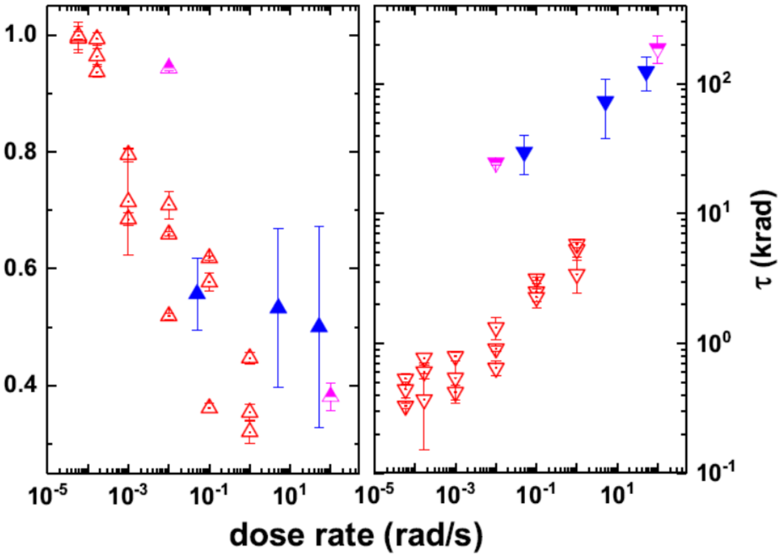
工艺差异的物理起源

干氧工艺实验结果

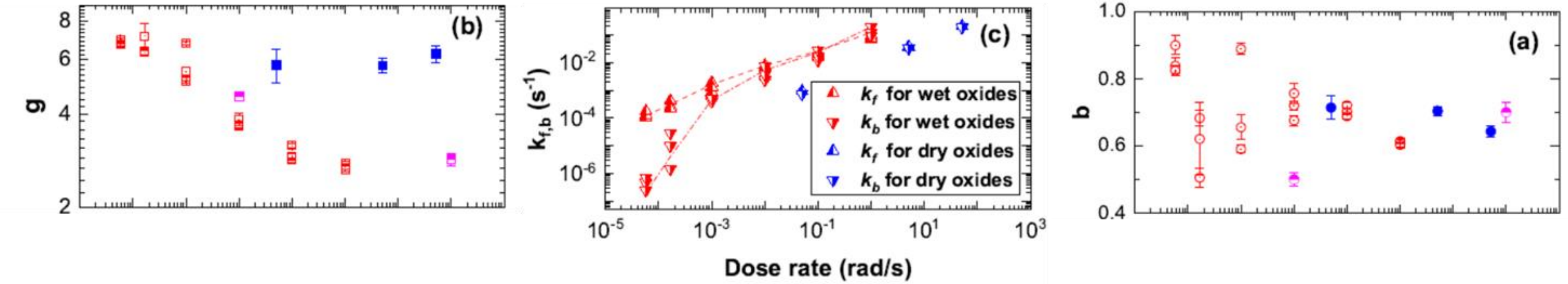


- ✓ 特征转化剂量增大是干氧剂量率效应的主要原因
- ✓ 湿氧以俘获产生机制为主，是可逆反应，表现显著的剂量率依赖
- ✓ 干氧以分裂产生机制为主，是不可逆反应，与剂量率几乎无关





计算困境的解决



$$\frac{dn}{dt} = \nabla \cdot (\mu_n n \vec{E} + D_n \nabla n) + G_n - R_n$$

$$\frac{dp}{dt} = -\nabla \cdot (\mu_p p \vec{E} - D_p \nabla p) + G_p - R_p$$

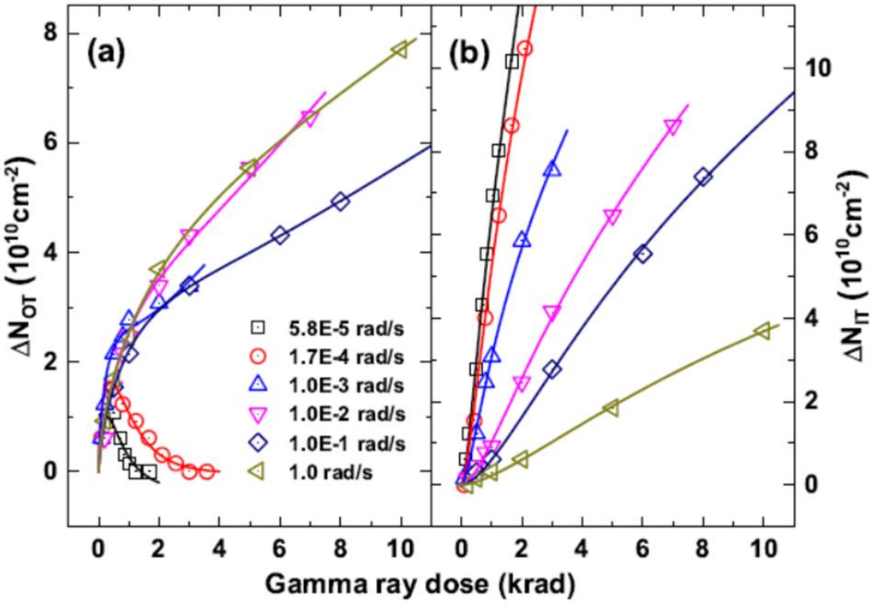
$$\frac{dT_i}{dt} = G_i - R_i$$

$$\frac{dH_2}{dt} = \nabla \cdot (D_{H_2} \nabla H_2) + G_{H_2} - R_{H_2}$$

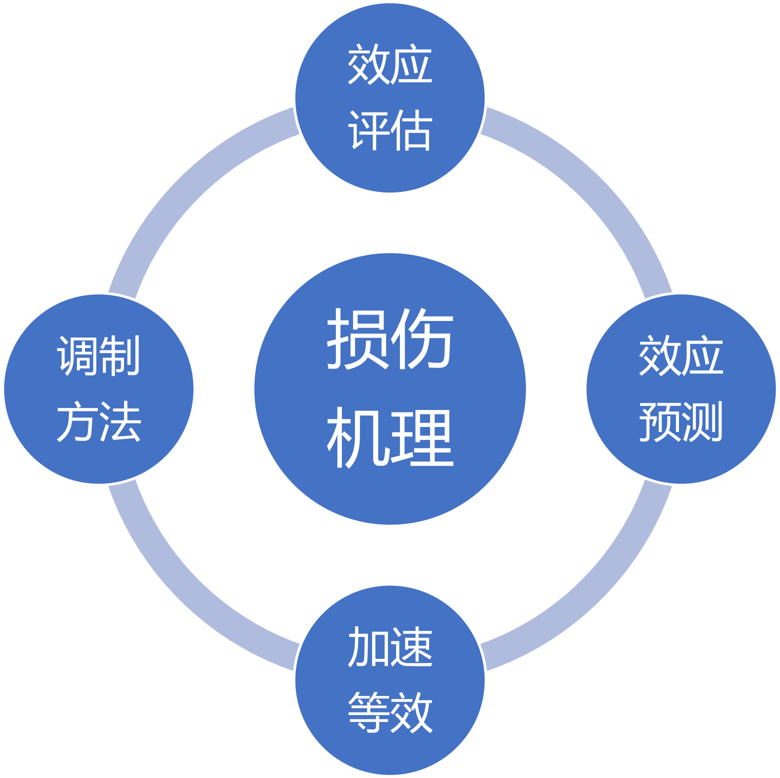
$$\frac{dH^+}{dt} = -\nabla \cdot (\mu_{H^+} H^+ \vec{E} - D_{H^+} \nabla H^+) + G_{H^+} - R_{H^+}$$

$$V_O(D) = (1-\lambda) g_e D^b + \lambda g_e D_c^b b e^{-\frac{D}{D_c}} \Gamma[b, 0, D/D_c],$$

$$P_b(D) = \lambda g_e D^b - \lambda g_e D_c^b b e^{-\frac{D}{D_c}} \Gamma[b, 0, D/D_c].$$



机理研究的作用



损伤机理

效应评估

效应预测

加速等效

调制方法

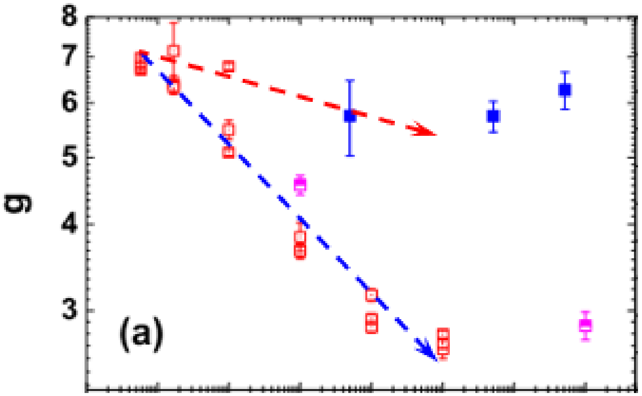
Part I 的主要内容

电离缺陷动力学机理

- 学界标准模型
- 物理困境与计算困难
- 新近发展
- 研究展望

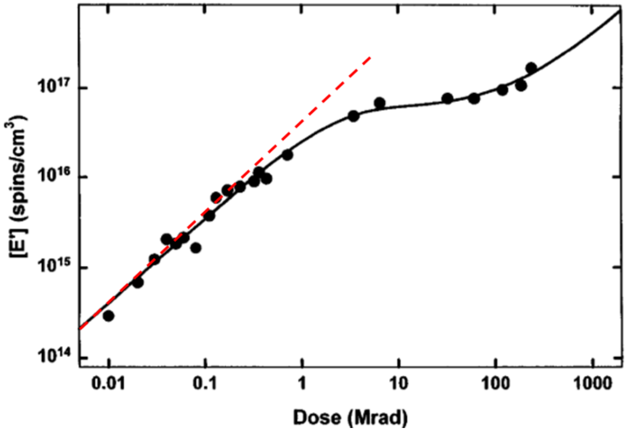
研究展望

□ 剂量率依赖的机理和模型



□ 大剂量的动力学模型

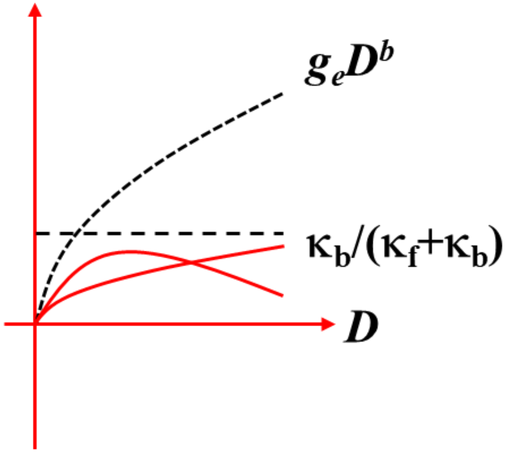
□ 温度依赖的机理和模型



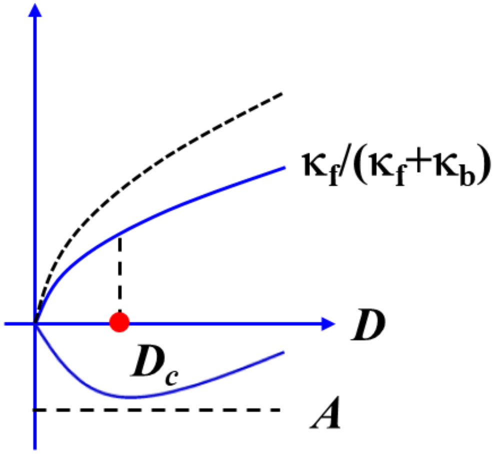
硅基器件的辐照损伤机理

宋 宇

内江师范学院



oxygen vacancies in bulk



dangling bonds at interface

Energy Loss by Particles Incident on Semiconductor Materials and Devices

Total Energy Loss = Ionizing + Nonionizing Losses

- **Incident energetic particles lose energy to ionizing and nonionizing processes**
  - **Ionizing processes produce electron-hole pairs**
  - **Nonionizing processes displace atoms**
- **Ionizing energy loss creates free charge, which alters material and device properties**
- **Nonionizing energy loss creates displacement damage, which alters material and device properties**

主要参考文献：两篇综述文章

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 50, NO. 3, JUNE 2003 653

Review of Displacement Damage Effects in Silicon Devices

J. R. Srour, *Fellow, IEEE*, Cheryl J. Marshall, *Member, IEEE*, and Paul W. Marshall, *Member, IEEE*

2013 IEEE NSREC
Short Course

Lessons Learnt From Our Past

Section II

Displacement Damage Effects in Devices

Dr. Joseph R. Srour
The Aerospace Corporation

Dr. James W. Palko
Stanford University

NSREC: Nuclear and Space Radiation Effect Conference

位移损伤环境

What Radiation Environments Produce Displacement Damage?

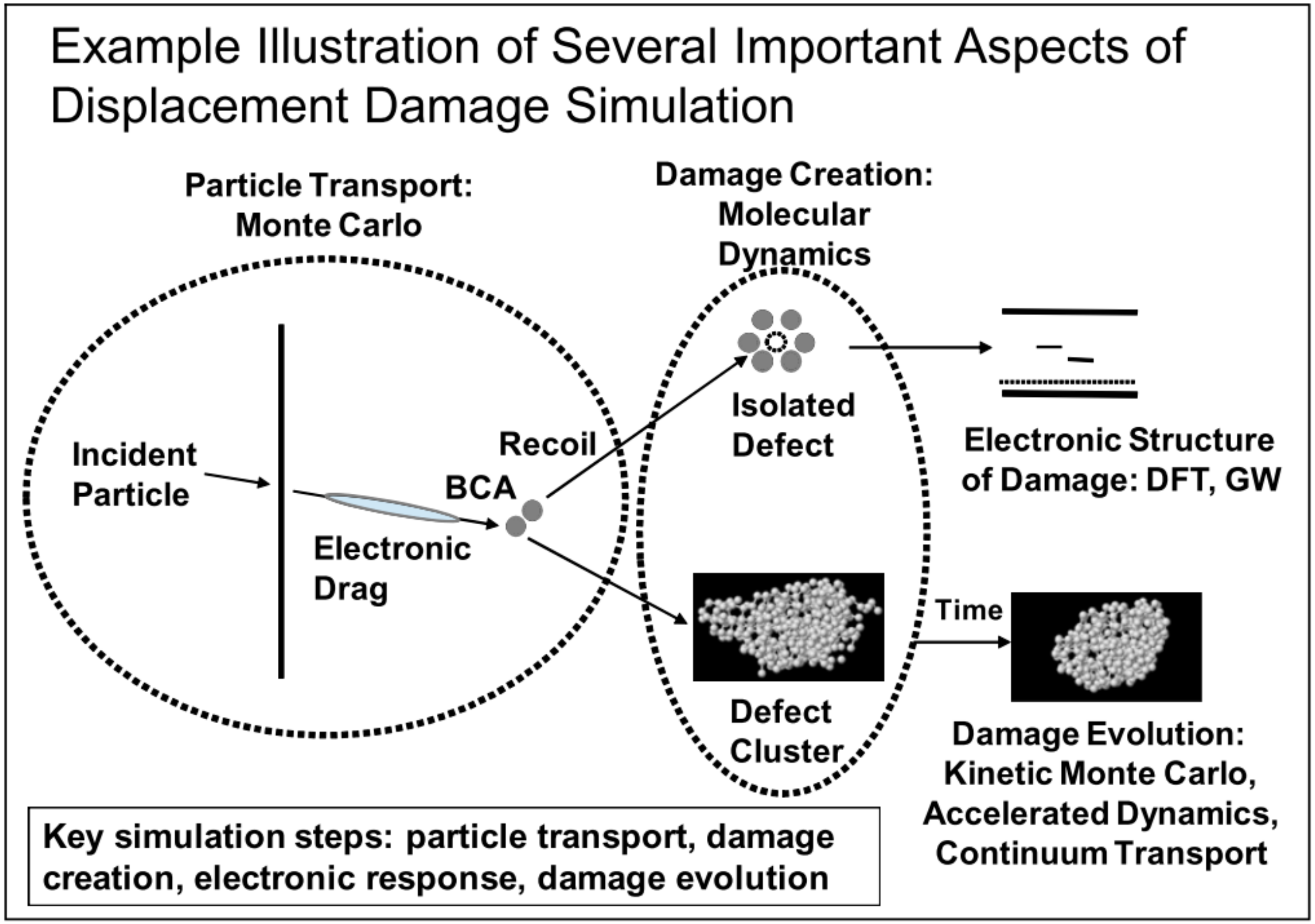
- **Space Radiation Environment**
  - *Trapped electrons*
  - *Trapped protons*
  - *Solar protons*
  - *Other Ions*
  - *Neutrons*
- **Nuclear Reactors**
  - *Neutrons*
- **Particle Accelerators**
  - *Protons and other ions*
  - *Pions*
  - *Et cetera*

伽马射线产生的二次电子

Large Hadron Collider at CERN

与半导体离子注入具有相似性

The big picture



Example Illustration of Several Important Aspects of Displacement Damage Simulation

Key simulation steps: particle transport, damage creation, electronic response, damage evolution

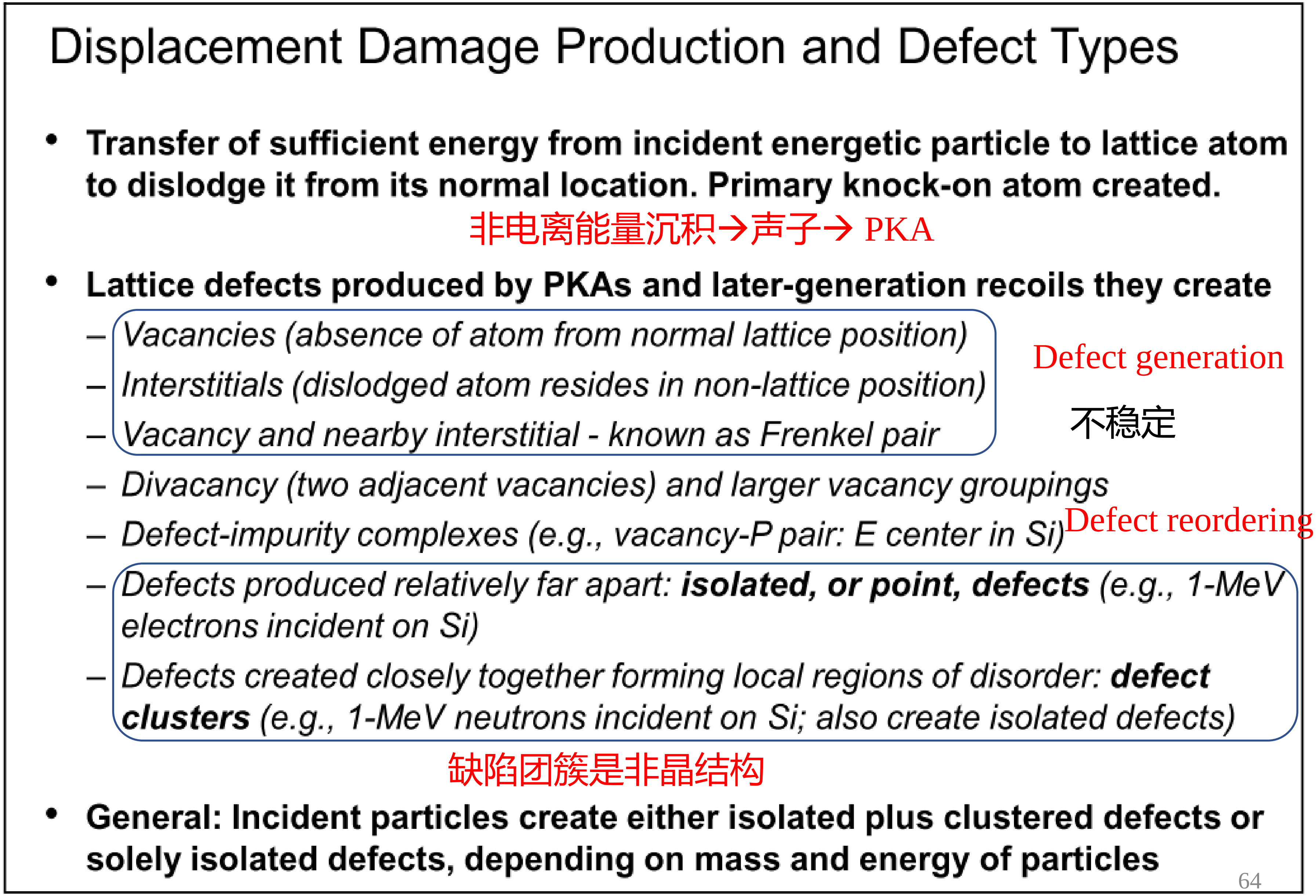
- ✓ 在辐射作用下，半导体中原子偏离原来所在的晶格位置
- ✓ 在半导体禁带中引入新的能级
- ✓ 改变少子寿命等半导体性质
- ✓ 造成材料和器件的电学、光学性质退化

报告题纲

Part II: 硅基器件位移损伤的机理

- ✓ 位移缺陷的产生与退火机理
- ✓ 位移损伤效应机理
- ✓ 新近发展与研究展望

位移缺陷的缺陷类型和产生过程



Displacement Damage Production and Defect Types

- **Transfer of sufficient energy from incident energetic particle to lattice atom to dislodge it from its normal location. Primary knock-on atom created.**

非电离能量沉积→声子→ PKA

- **Lattice defects produced by PKAs and later-generation recoils they create**
  - *Vacancies (absence of atom from normal lattice position)*
  - *Interstitials (dislodged atom resides in non-lattice position)*
  - *Vacancy and nearby interstitial - known as Frenkel pair*

Defect generation

不稳定

  - *Divacancy (two adjacent vacancies) and larger vacancy groupings*
  - *Defect-impurity complexes (e.g., vacancy-P pair: E center in Si)*

Defect reordering

  - *Defects produced relatively far apart: **isolated, or point, defects** (e.g., 1-MeV electrons incident on Si)*
  - *Defects created closely together forming local regions of disorder: **defect clusters** (e.g., 1-MeV neutrons incident on Si; also create isolated defects)*

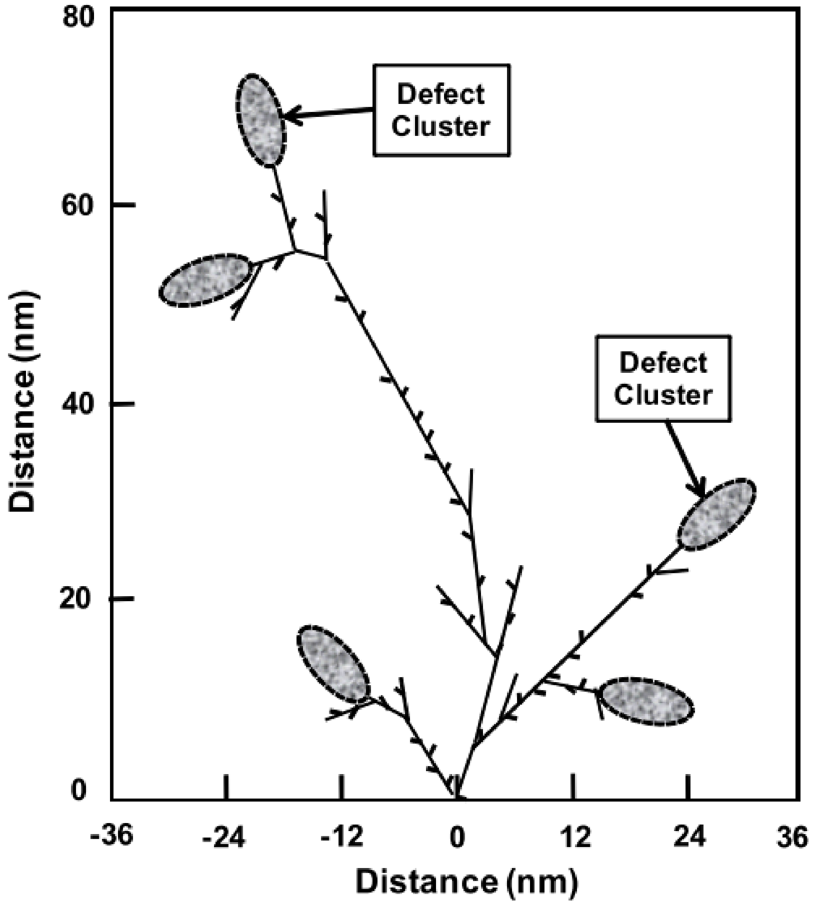
缺陷团簇是非晶结构

- **General: Incident particles create either isolated plus clustered defects or solely isolated defects, depending on mass and energy of particles**

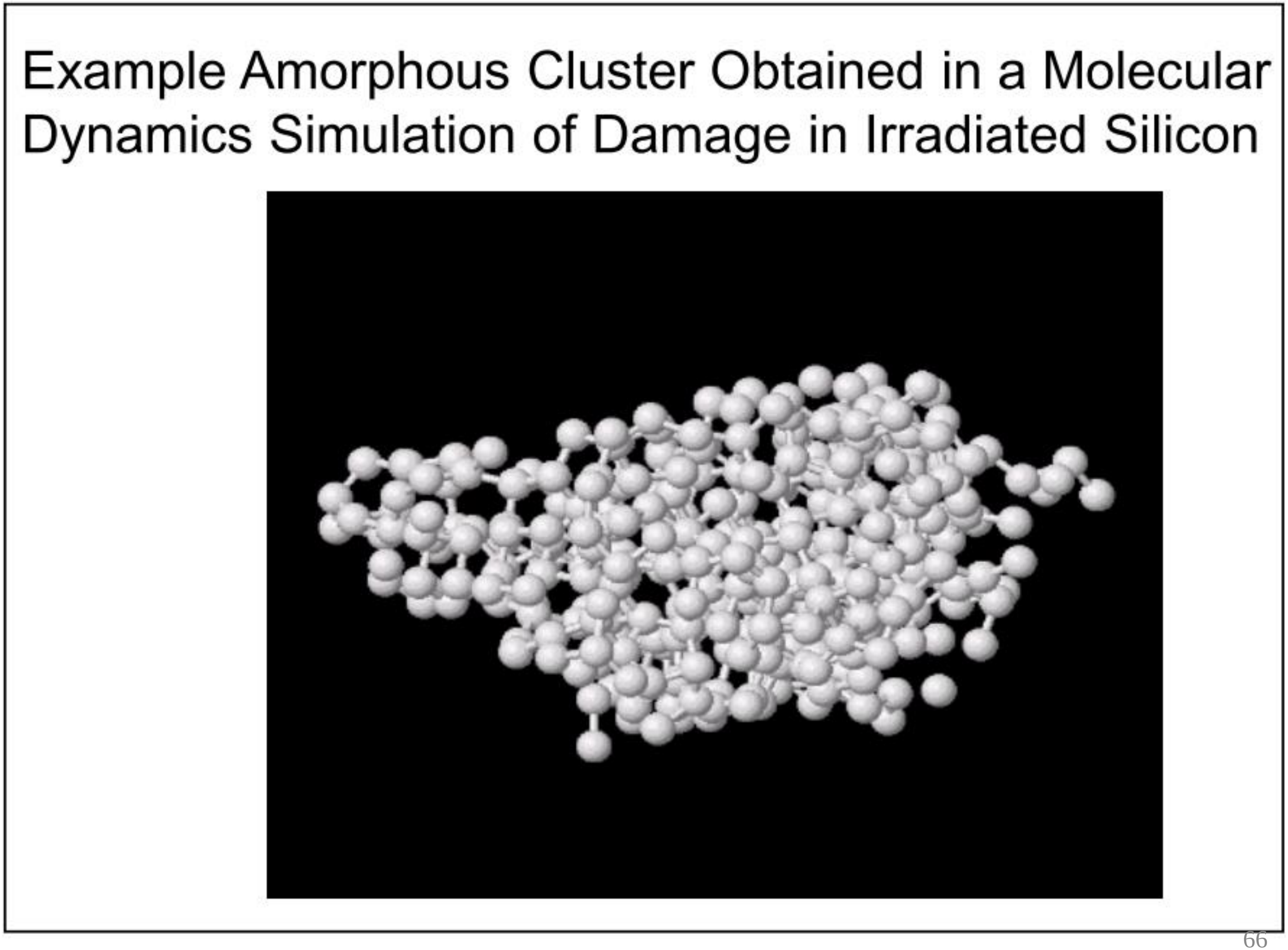
缺陷产生过程

Conceptual Illustration of Damage Produced in Silicon by a 50-keV Primary Recoil Atom

- Production of small defect clusters and isolated defects is shown



缺陷团簇的非晶结构



Example Amorphous Cluster Obtained in a Molecular Dynamics Simulation of Damage in Irradiated Silicon

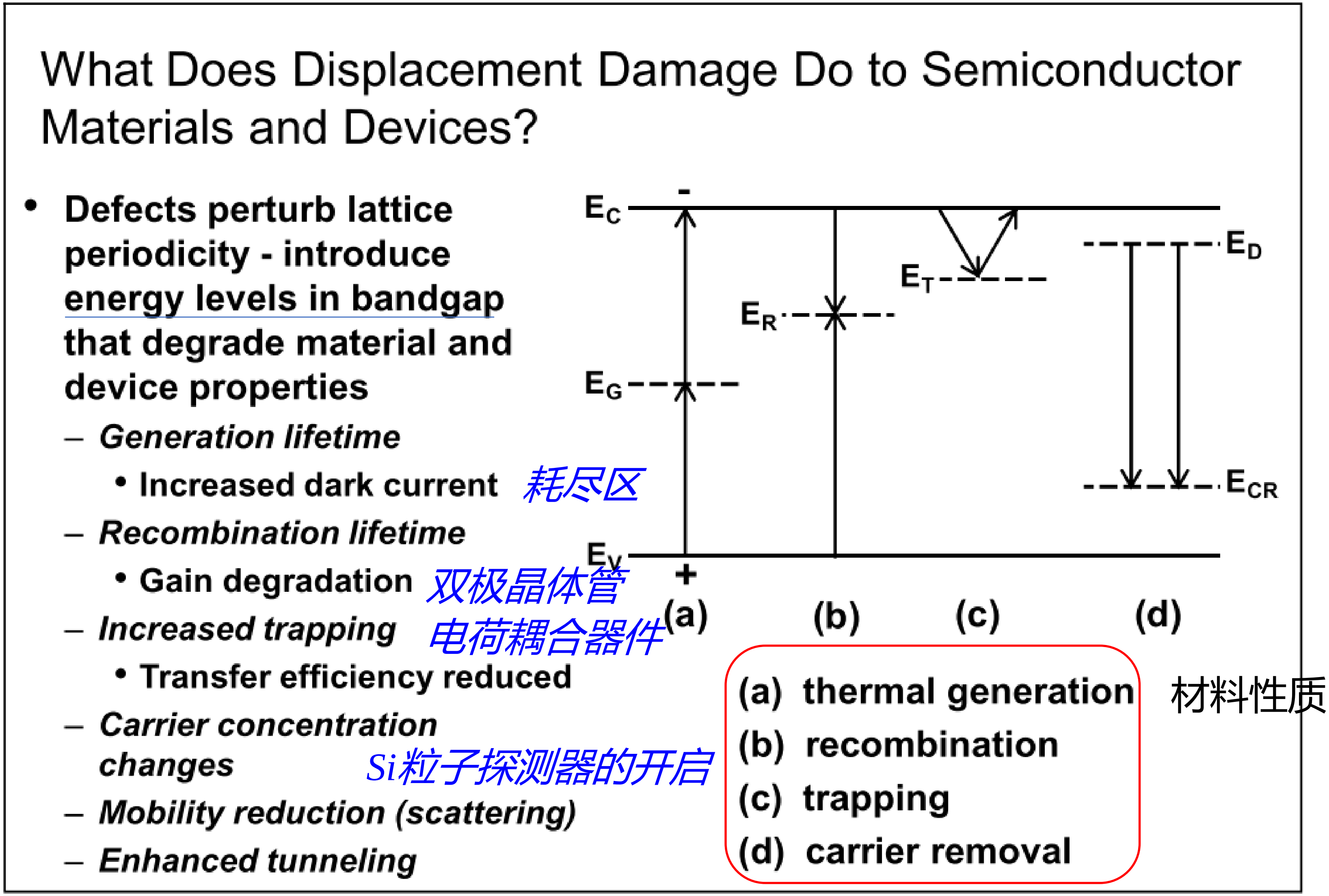
报告题纲

Part II: 硅基器件位移损伤的机理

- ✓ 位移缺陷的产生与退火机理
- ✓ 位移损伤效应机理
- ✓ 新近发展与研究展望

位移缺陷对材料、器件性质的影响

器件性质



What Does Displacement Damage Do to Semiconductor Materials and Devices?

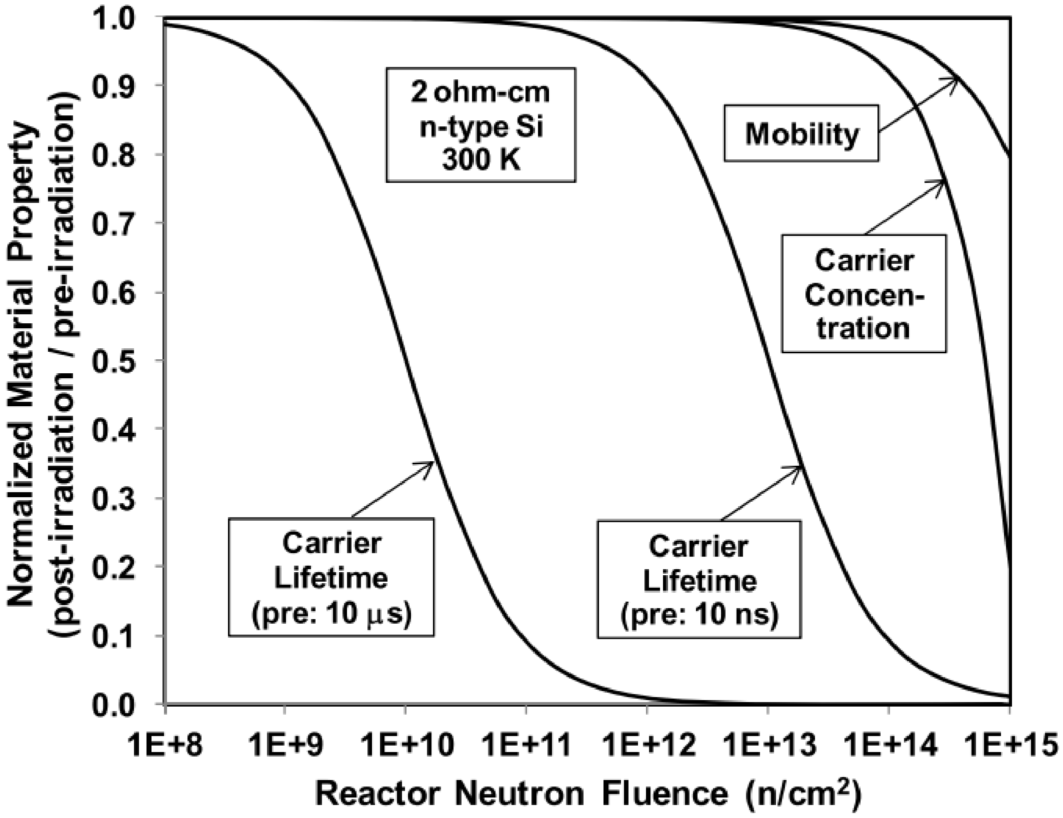
- **Defects perturb lattice periodicity - introduce energy levels in bandgap that degrade material and device properties**
  - ***Generation lifetime***
    - **Increased dark current** *耗尽区*
  - ***Recombination lifetime***
    - **Gain degradation** *双极晶体管*
  - ***Increased trapping*** *电荷耦合器件*
    - **Transfer efficiency reduced**
  - ***Carrier concentration changes*** *Si粒子探测器的开启*
  - ***Mobility reduction (scattering)***
  - ***Enhanced tunneling***

(a) thermal generation
(b) recombination
(c) trapping
(d) carrier removal

材料性质

材料性质的相对敏感性

Relative Sensitivity of Si Electrical Properties to Neutrons

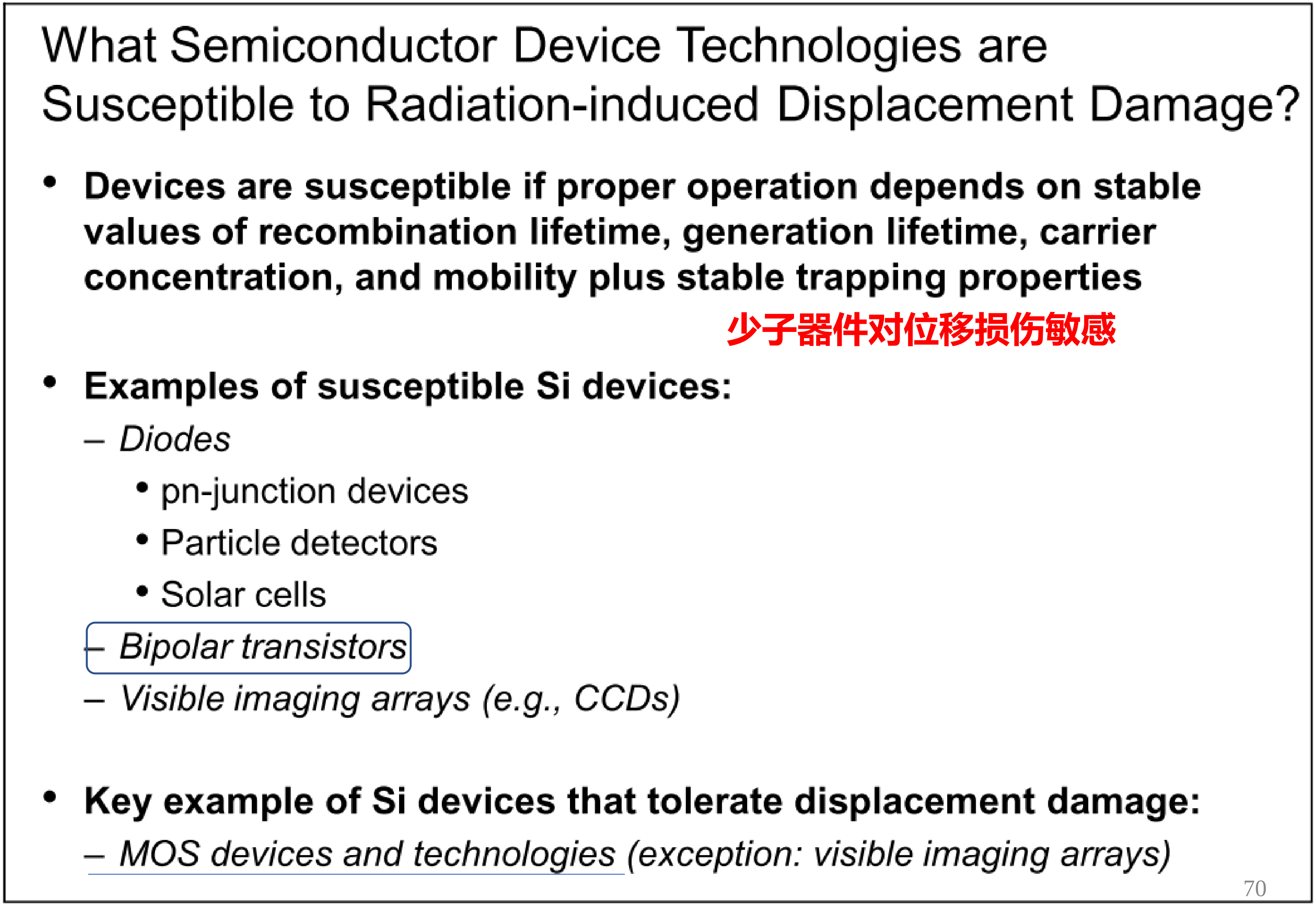


- Significant displacement damage is needed to affect the recombination lifetime when the pre-irradiation value is short

✓ 载流子寿命最敏感

✓ 好的容易变坏，坏的不容易变得更坏！

器件的抗辐射特性



What Semiconductor Device Technologies are Susceptible to Radiation-induced Displacement Damage?

- **Devices are susceptible if proper operation depends on stable values of recombination lifetime, generation lifetime, carrier concentration, and mobility plus stable trapping properties**

少子器件对位移损伤敏感

- **Examples of susceptible Si devices:**
  - *Diodes*
    - pn-junction devices
    - Particle detectors
    - Solar cells
  - *Bipolar transistors*
  - *Visible imaging arrays (e.g., CCDs)*

- **Key example of Si devices that tolerate displacement damage:**
  - *MOS devices and technologies (exception: visible imaging arrays)*

报告题纲

Part II: 硅基器件位移损伤的机理

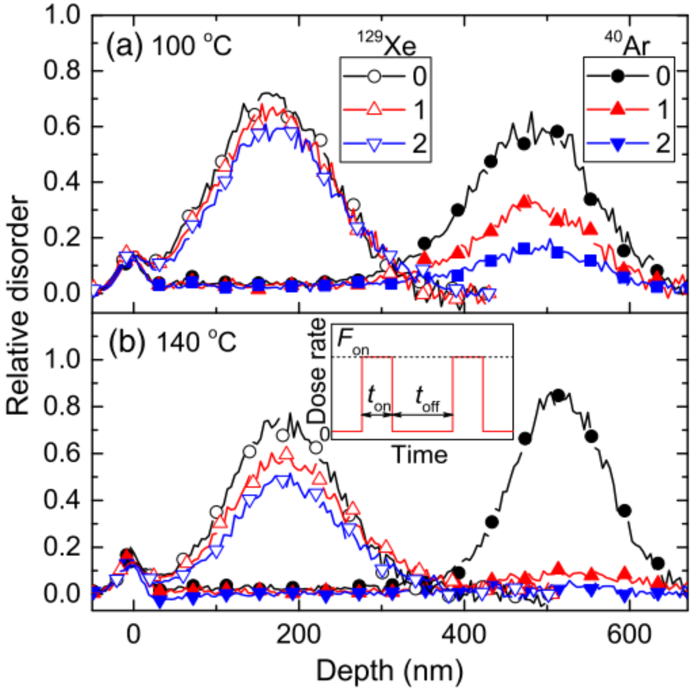
- ✓ 位移缺陷的产生与退火机理
- ✓ 位移损伤效应机理
- ✓ 新近发展与研究展望

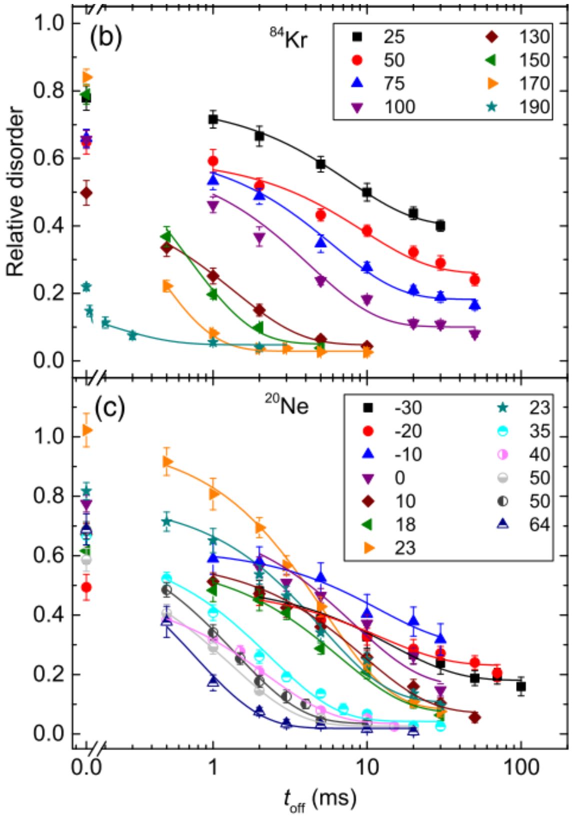
碰撞级联密度在缺陷动力学中的重要作用

PHYSICAL REVIEW LETTERS **120,** 216101 (2018)

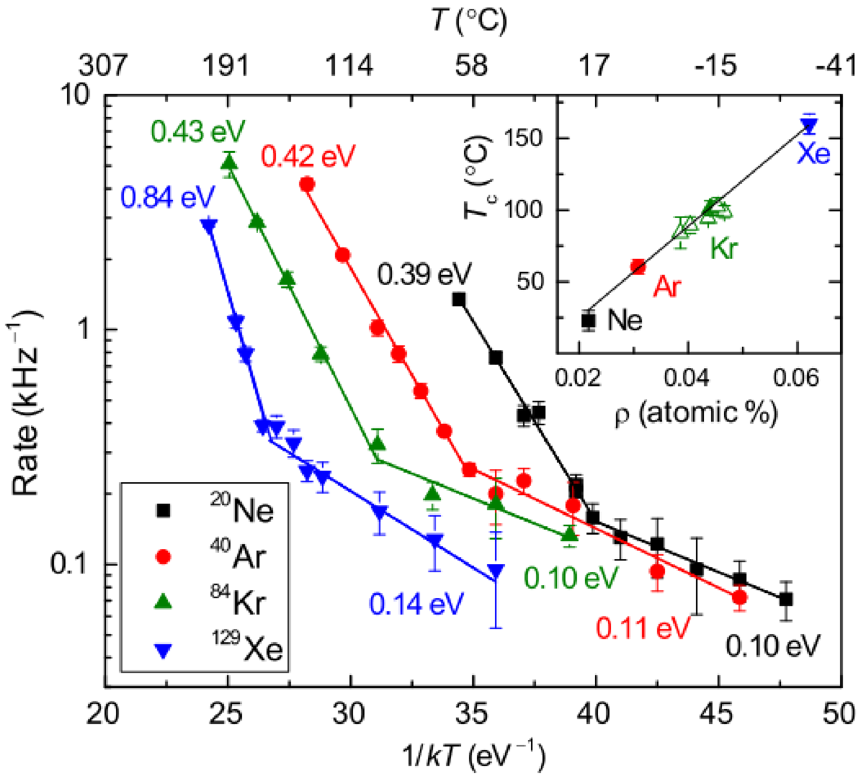
Deterministic Role of Collision Cascade Density in Radiation Defect Dynamics in Si

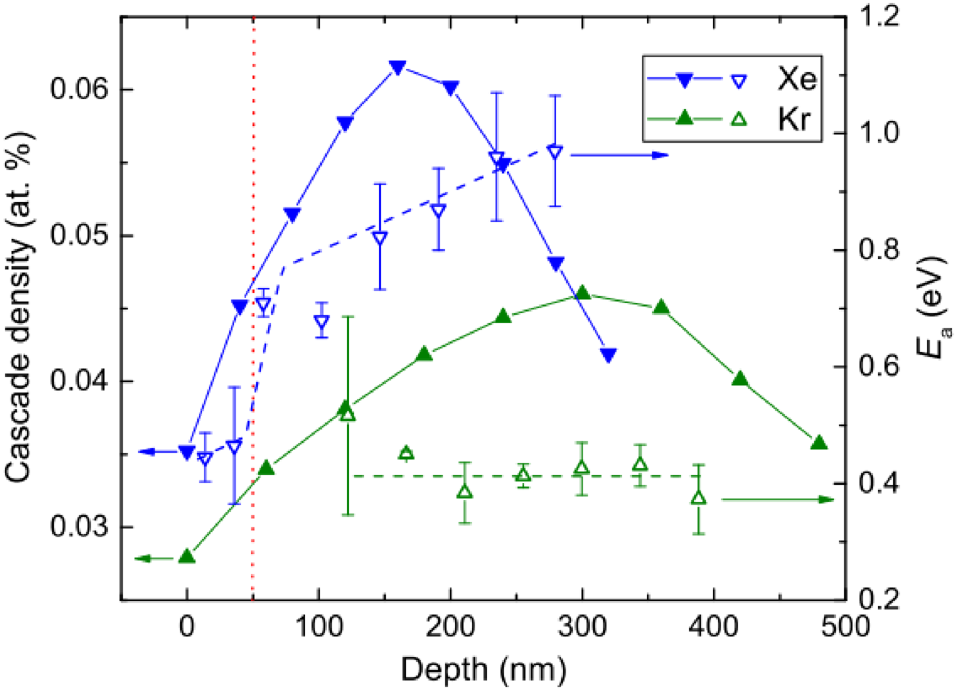
J. B. Wallace,[1,2] L. B. Bayu Aji,[1] L. Shao,[2] and S. O. Kucheyev[1,*]
[1]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[2]*Department of Nuclear Engineering, Texas A&M University, College Station, Texas 77843, USA*





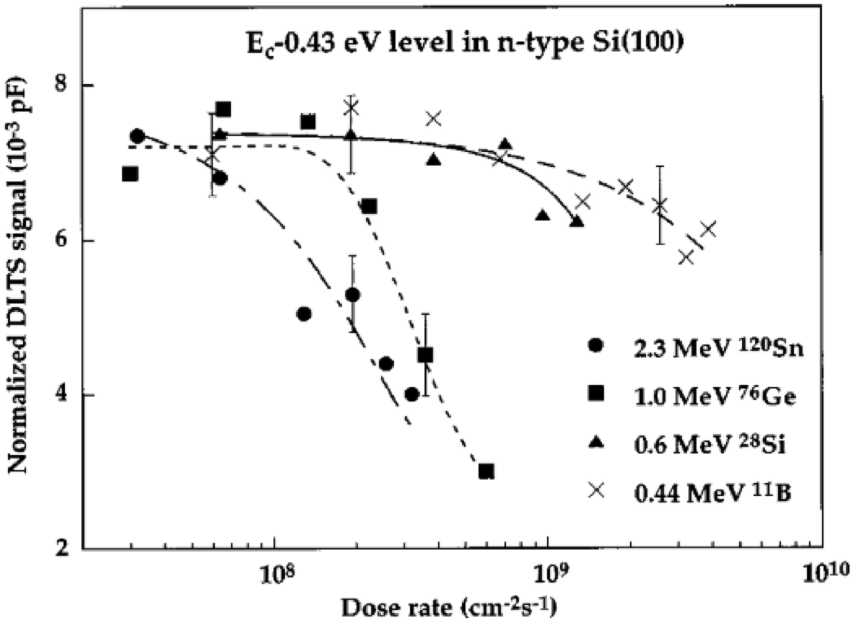
碰撞级联密度在缺陷动力学中的重要作用

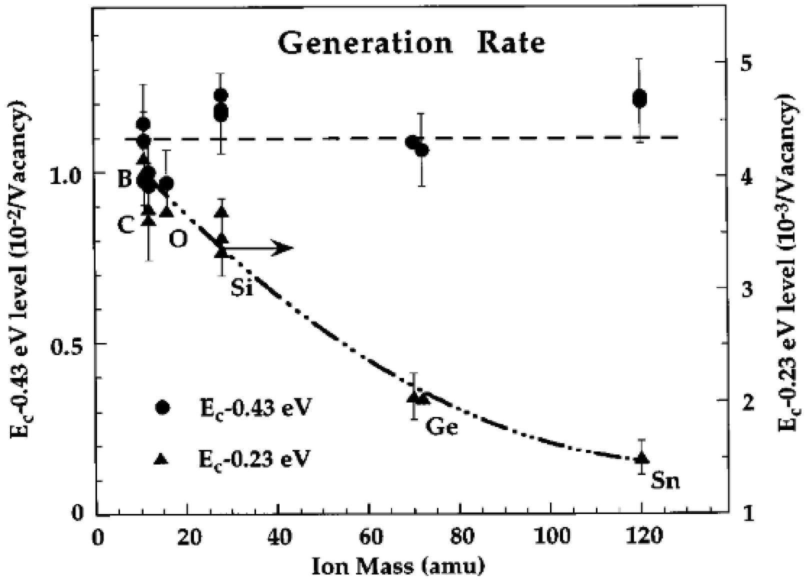




当级联密度超过~0.04 at.%，高温区的激活能增大，意味着动力学退火的主要过程改变

重要自由度：DD的注量率依赖



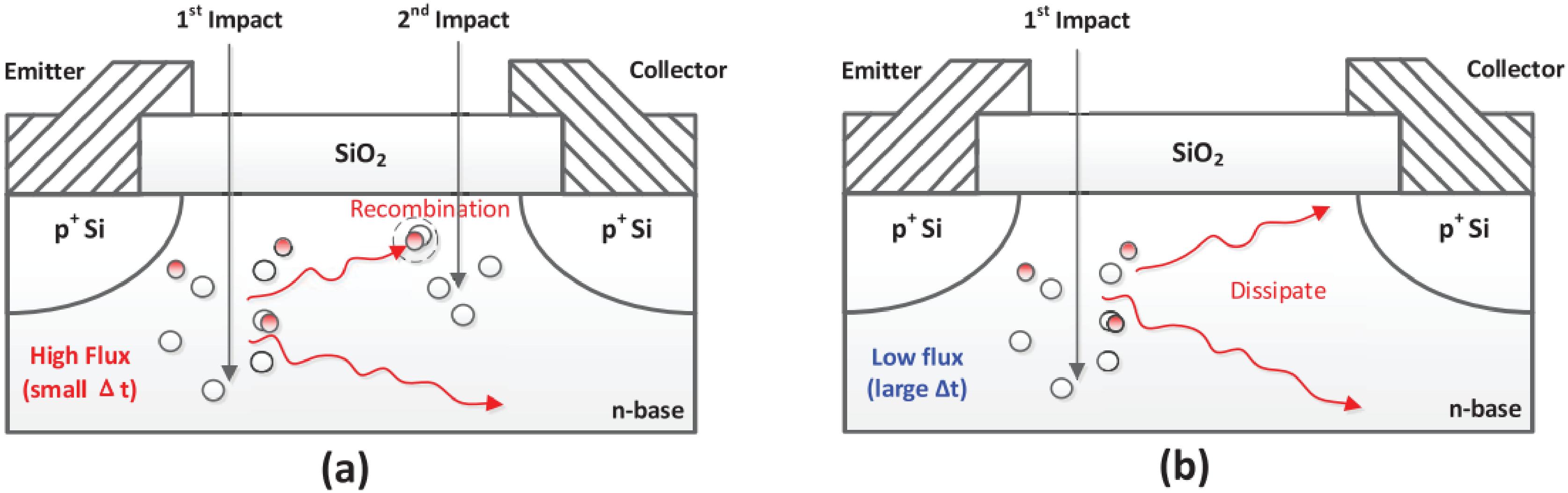


剂量率越高，产生缺陷越少

敏感剂量率区域与辐射粒子质量负相关

Svensson, B. G (1993). *Physical Review Letters*, *71*(12), 1860–1863 .
Svensson, B (1997). *Physical Review B*, *55*(16), 10498–10507.

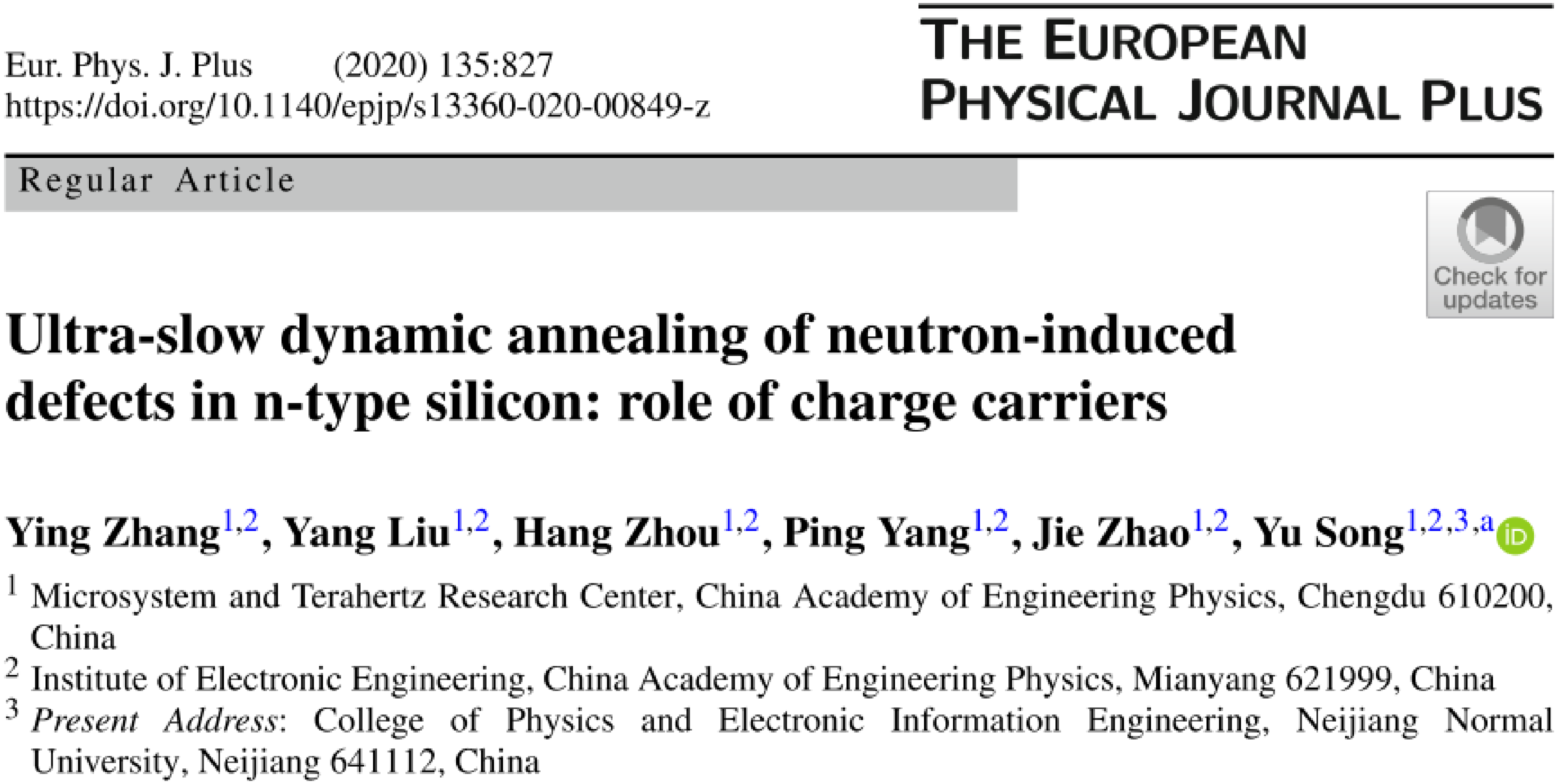
重要自由度：DD的注量率依赖



机理：自间隙原子的耗散

- ✓ 高注量率：自间隙原子耗散前与第二个缺陷团簇湮灭，减少系统中缺陷总数
- ✓ 低注量率：自间隙原子耗散，不影响系统缺陷总数
- ✓ 注量率越高，相同注量下，样品中缺陷总浓度越低

中子DD的注量率依赖—载流子的作用



Eur. Phys. J. Plus (2020) 135:827
https://doi.org/10.1140/epjp/s13360-020-00849-z

THE EUROPEAN
PHYSICAL JOURNAL PLUS

Regular Article

Ultra-slow dynamic annealing of neutron-induced defects in n-type silicon: role of charge carriers

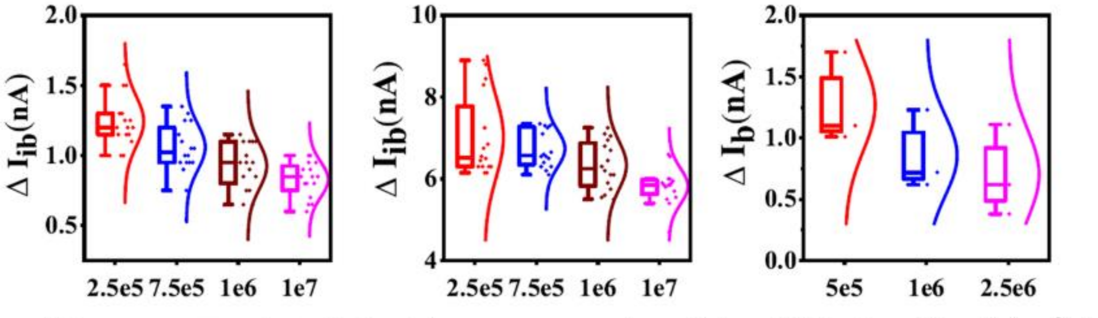
Ying Zhang[1,2], **Yang Liu**[1,2], **Hang Zhou**[1,2], **Ping Yang**[1,2], **Jie Zhao**[1,2], **Yu Song**[1,2,3,a]

[1] Microsystem and Terahertz Research Center, China Academy of Engineering Physics, Chengdu 610200, China
[2] Institute of Electronic Engineering, China Academy of Engineering Physics, Mianyang 621999, China
[3] *Present Address*: College of Physics and Electronic Information Engineering, Neijiang Normal University, Neijiang 641112, China

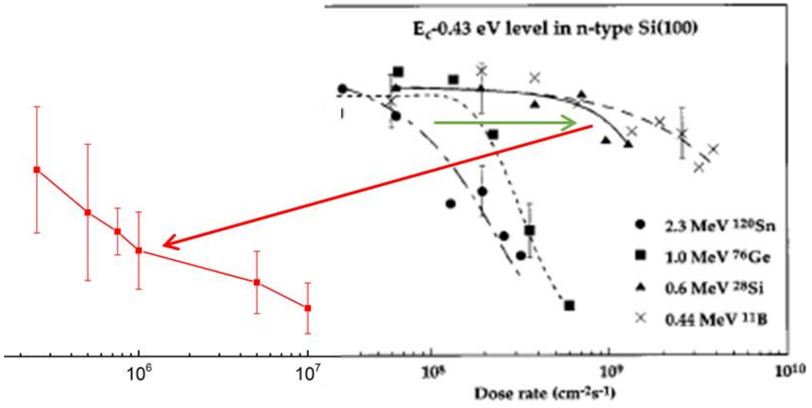
Editor of the journal: the scientific objectives of the work seem quite ambitious

中子DD的注量率依赖—载流子的作用

中子质量几乎等于质子，剂量率敏感区域应相似，但实验发现注量率敏感区域低4个数量级

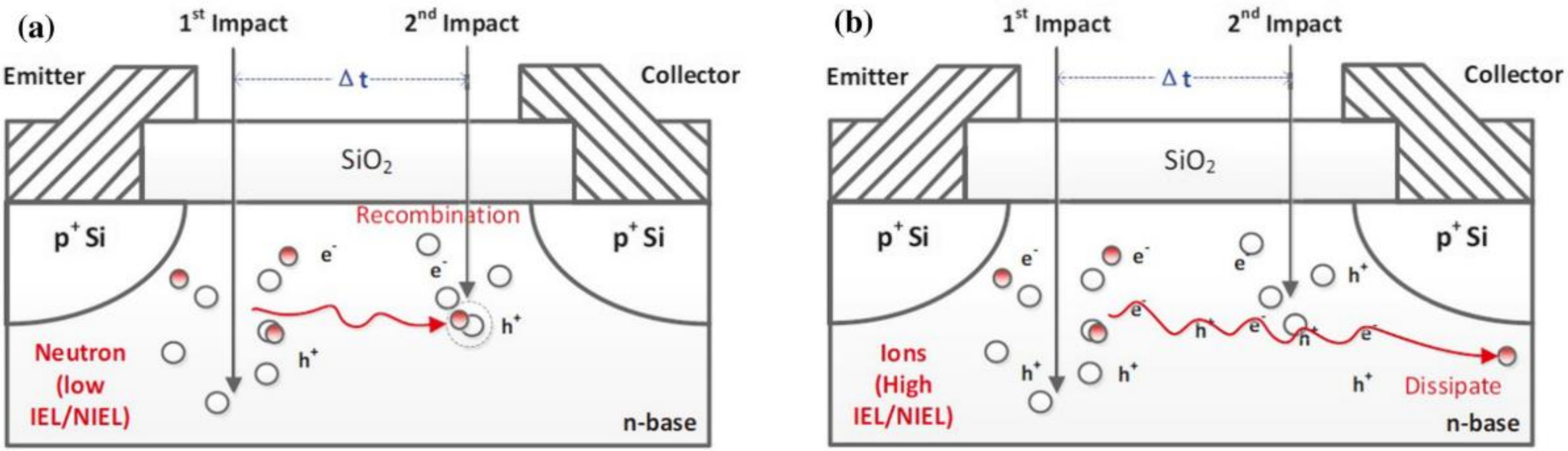


(b) Neutron Flux (n/cm²·s) (c) Neutron Flux (n/cm²·s) (d) Neutron Flux (n/cm²·s)



中子DD的注量率依赖—载流子的作用

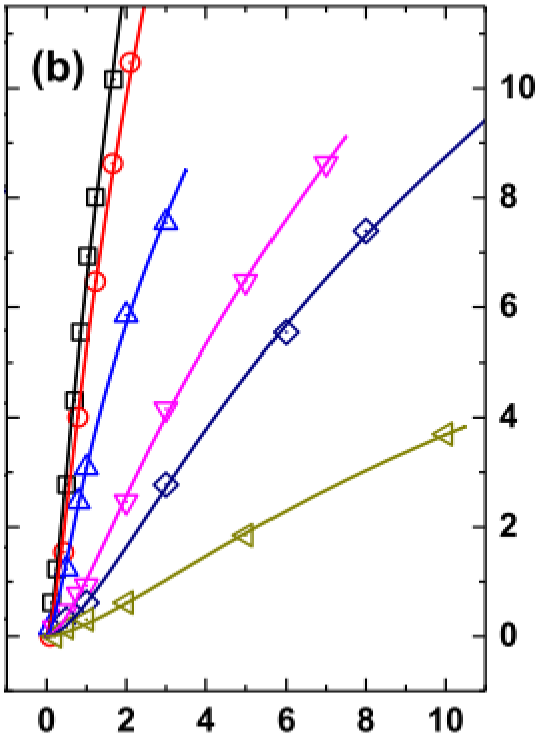
机理：粒子诱导载流子对其诱导位移缺陷动力学的加速作用



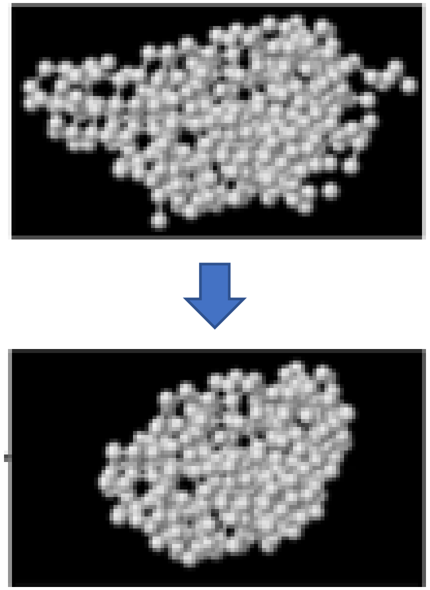
中子辐照：几乎无载流子，间隙原子扩散慢　质子辐照：大量载流子，间隙原子扩散快

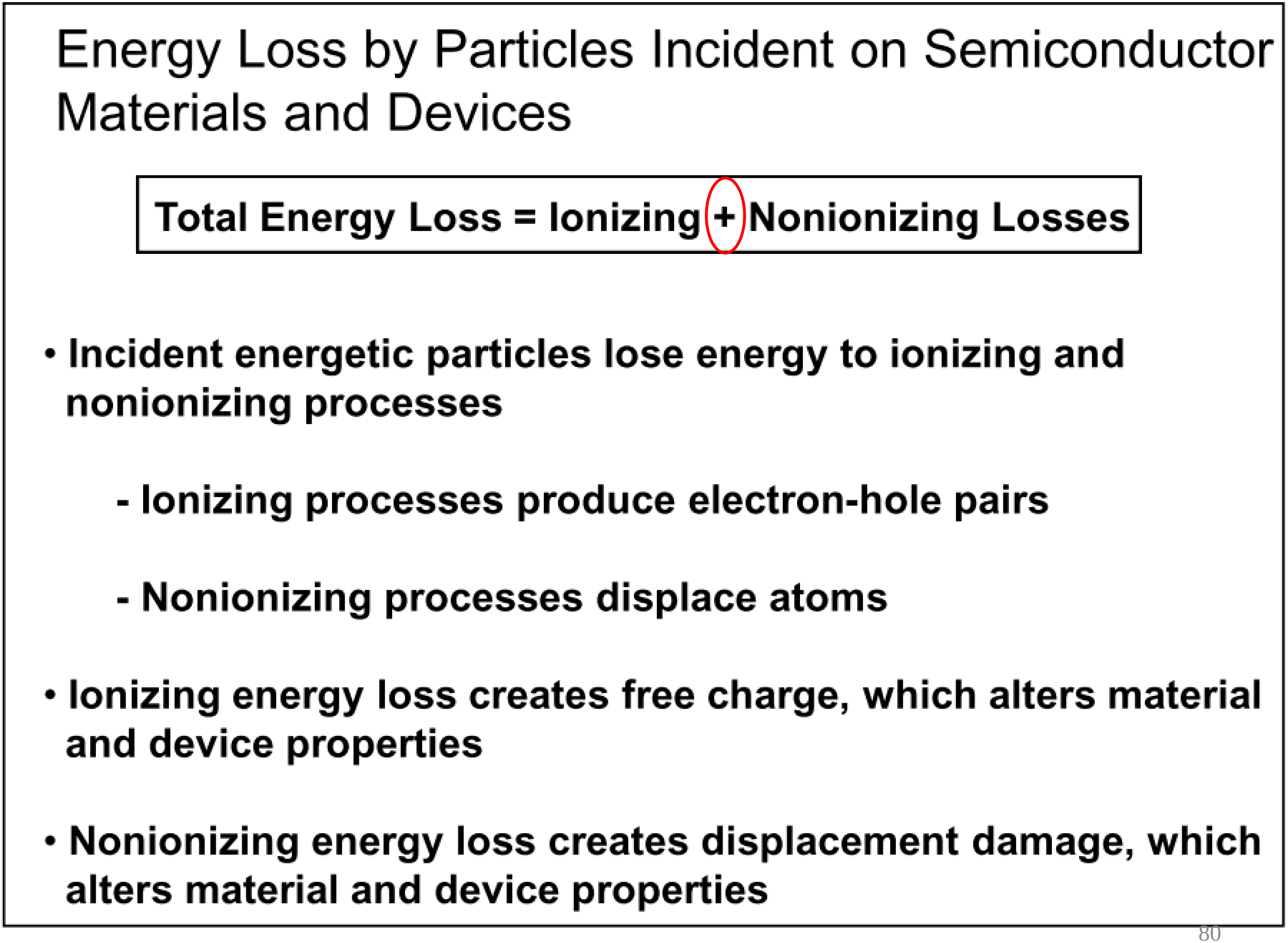
研究展望

实验方面：基于在线实验技术，获得位移损伤的注量依赖和注量率依赖行为



理论方面：缺陷团簇的电子性质和演化机制





Energy Loss by Particles Incident on Semiconductor Materials and Devices

Total Energy Loss = Ionizing + Nonionizing Losses

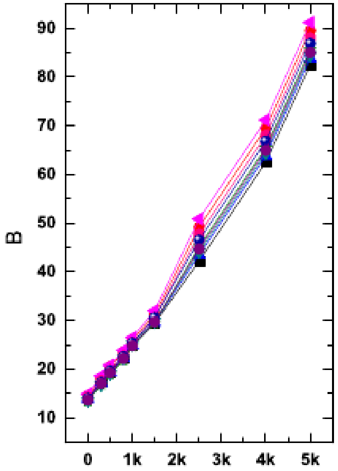
- **Incident energetic particles lose energy to ionizing and nonionizing processes**
  - **- Ionizing processes produce electron-hole pairs**
  - **- Nonionizing processes displace atoms**
- **Ionizing energy loss creates free charge, which alters material and device properties**
- **Nonionizing energy loss creates displacement damage, which alters material and device properties**

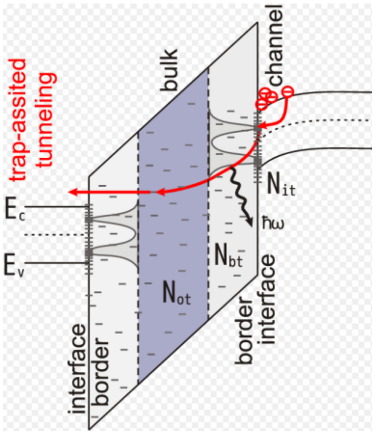
报告题纲

Part III: 硅基器件位移-电离辐照协同效应的机理

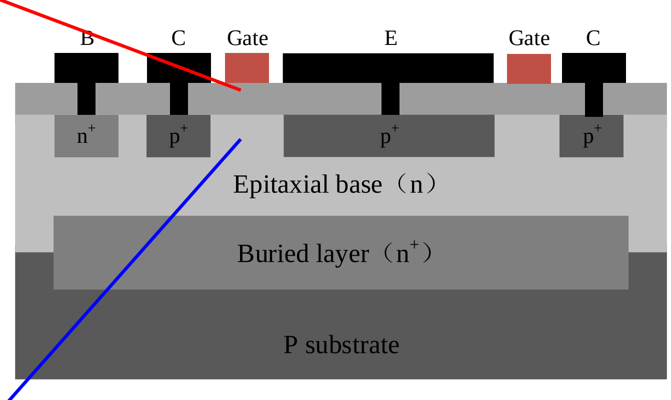
- ✓标准模型及存在问题
- ✓理论新发展
- ✓实验验证
- ✓研究展望

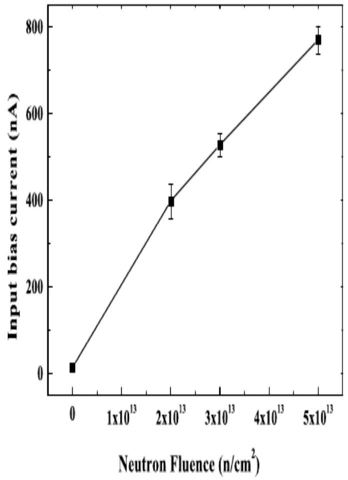
损伤分离依据：缺陷产生在不同区域

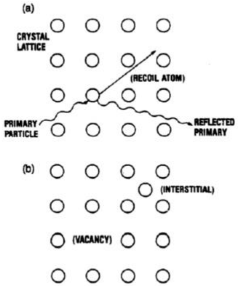


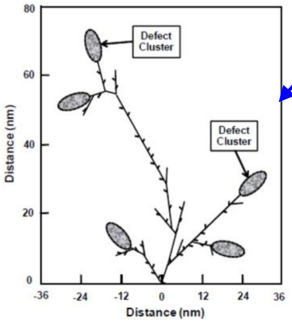


Gate oxide







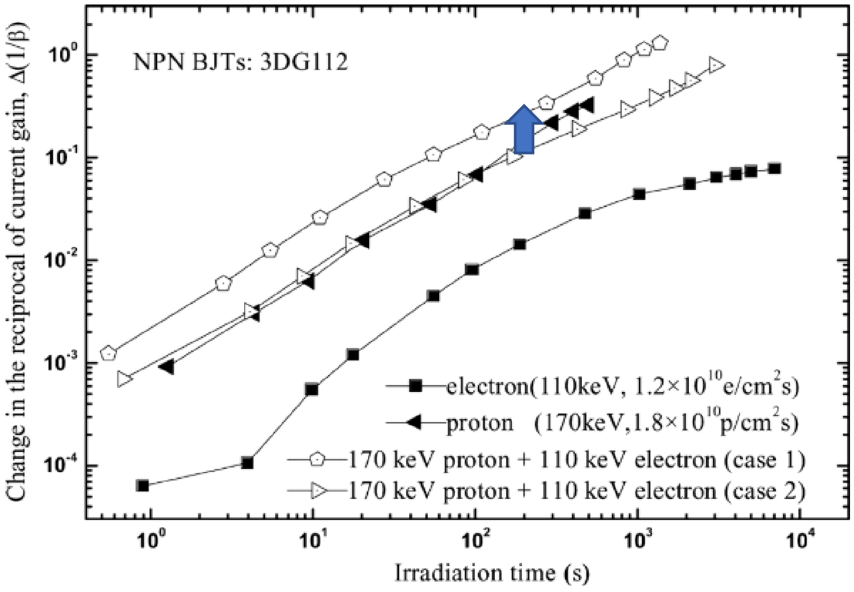


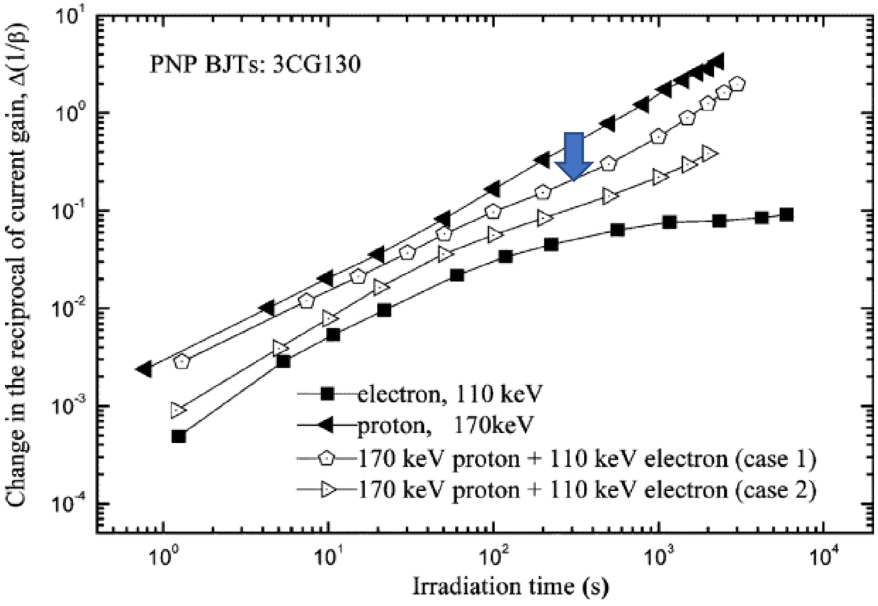
Bulk silicon

两者产生在器件的不同区域（氧化层、体硅），因此一般认为没有相互作用，可以分离

辐照协同效应及其极性

实验观察到实际损伤与简单求和。损伤有显著差异，可称为辐射协同效应(irradiation synergistic effect, ISE)





NPN: DD-ID > DD + ID

positive synergistic effect

Li, X., IEEE Transactions on Nuclear Science, 59(3 PART 2), 625–633.

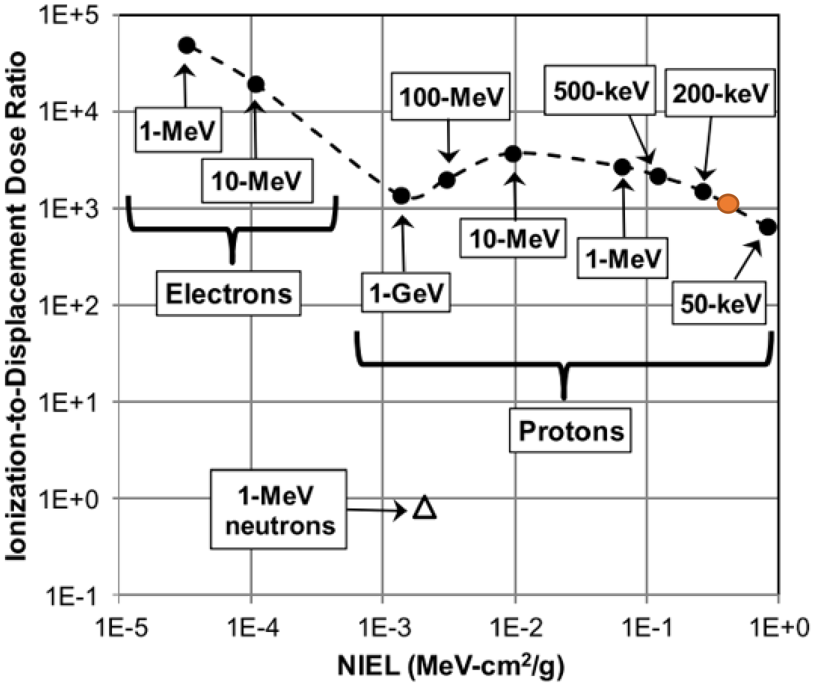
PNP: n-γ < n + γ

negative synergistic effect

Li, X., IEEE Transactions on Nuclear Science, 59(2), 439–446.

实验研究的不足

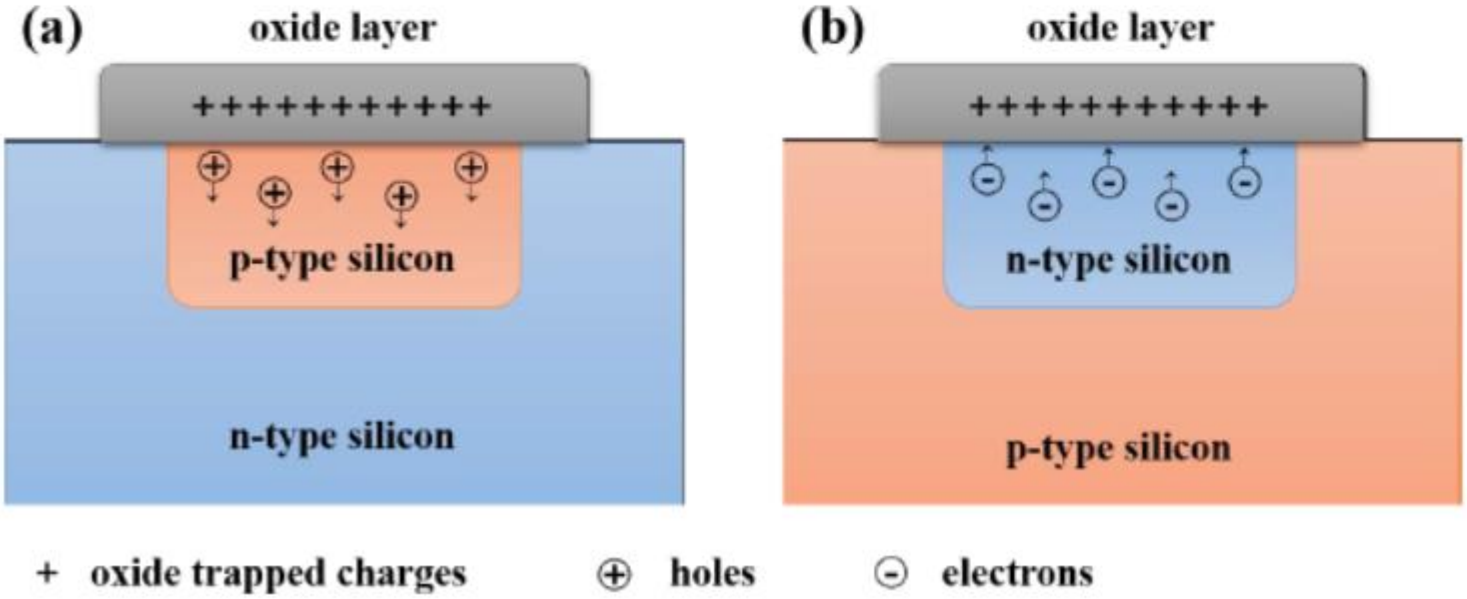
- ✓ 110keV 电子产生纯电离损伤，但170keV 质子同时产生位移损伤和电离损伤，难以确定协同效应的大小



- ✓ 电离剂量、位移注量往往固定，可能只观察到了冰山一角

现状1：辐照协同效应的行为不清楚

“标准”图像：OT对硅中载流子的库伦作用

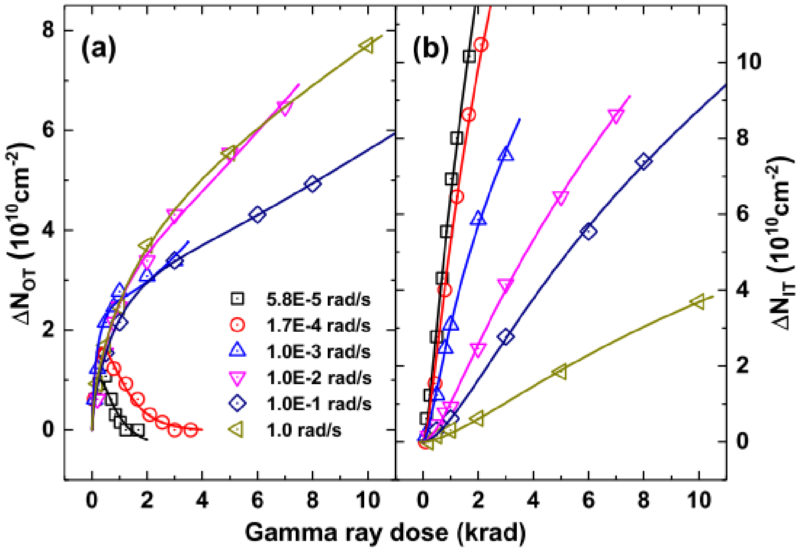


$$R = r \cdot n_i^2 \cdot \exp - \frac{E_F^h - E_F^e}{kT}$$

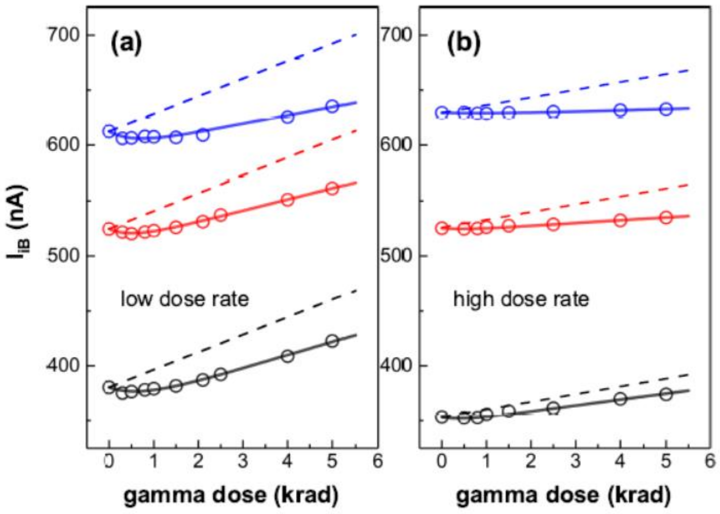
- ✓ NPN晶体管：ot排斥p型硅中空穴，载流子浓度差异变小，复合增强，正的协同效应
- ✓ PNP晶体管：ot吸引n型硅中电子，载流子浓度差异增大，复合减弱，负的协同效应

IEEE Trans.Nucl.Sci.,49, 2643 (2002).

“标准”图像存在问题：剂量率依赖



- ✓ 相同总剂量下，剂量率越低，氧化物中固定电荷越少，库伦效应应该越弱
- ✓ 实际情况完全相反：低剂量率下PNP晶体管表现出更强的协同减弱效应



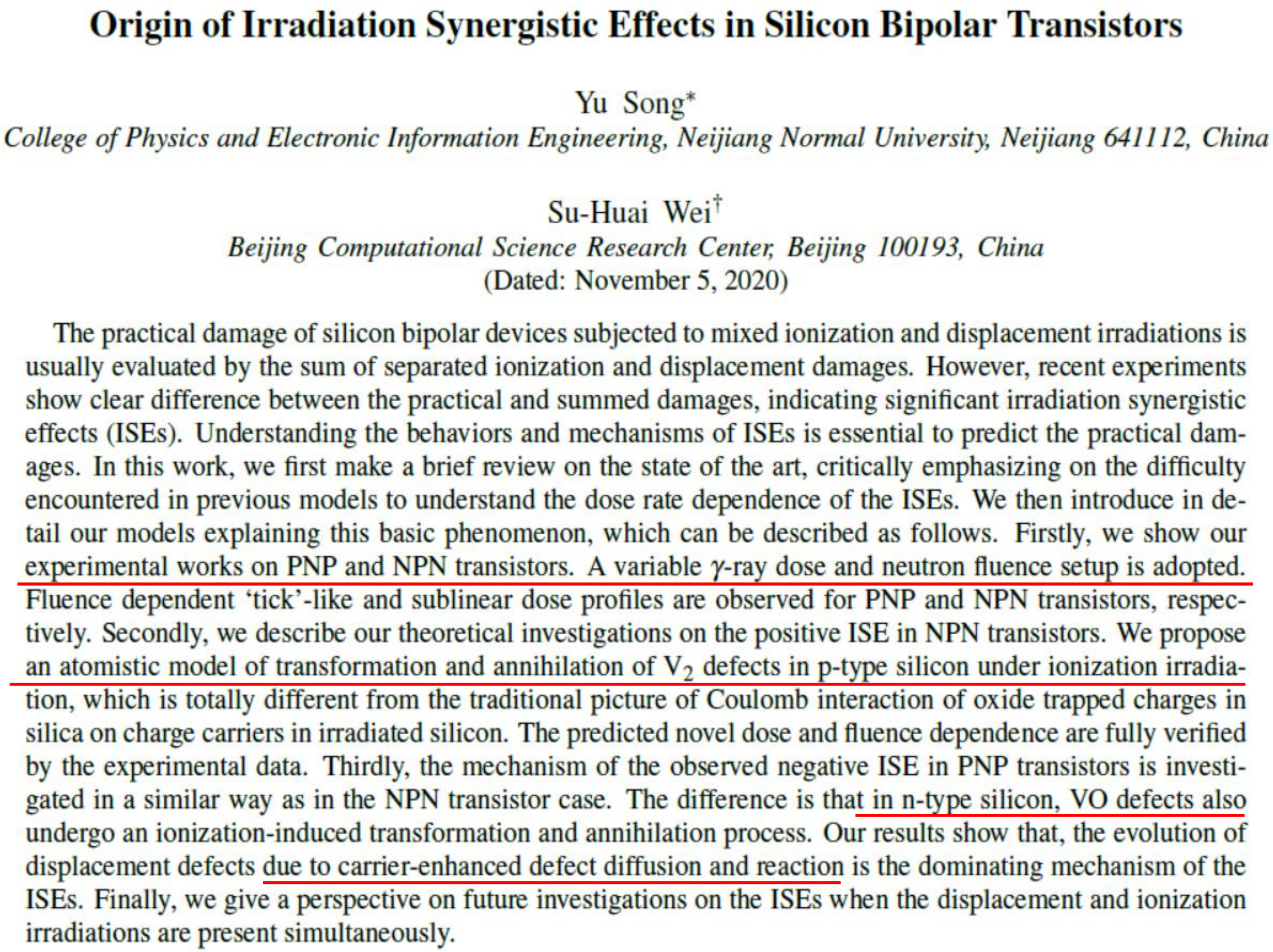
现状2：库伦相互作用机理不是辐照协同效应的主要原因

报告题纲

Part III: 硅基器件位移-电离辐照协同效应的机理

✓ 标准模型及存在问题
✓ 理论新发展
✓ 实验验证
✓ 研究展望

新发展：Ionization-irradiation-induced evolution of displacement defects in Si



Origin of Irradiation Synergistic Effects in Silicon Bipolar Transistors

Yu Song*
College of Physics and Electronic Information Engineering, Neijiang Normal University, Neijiang 641112, China

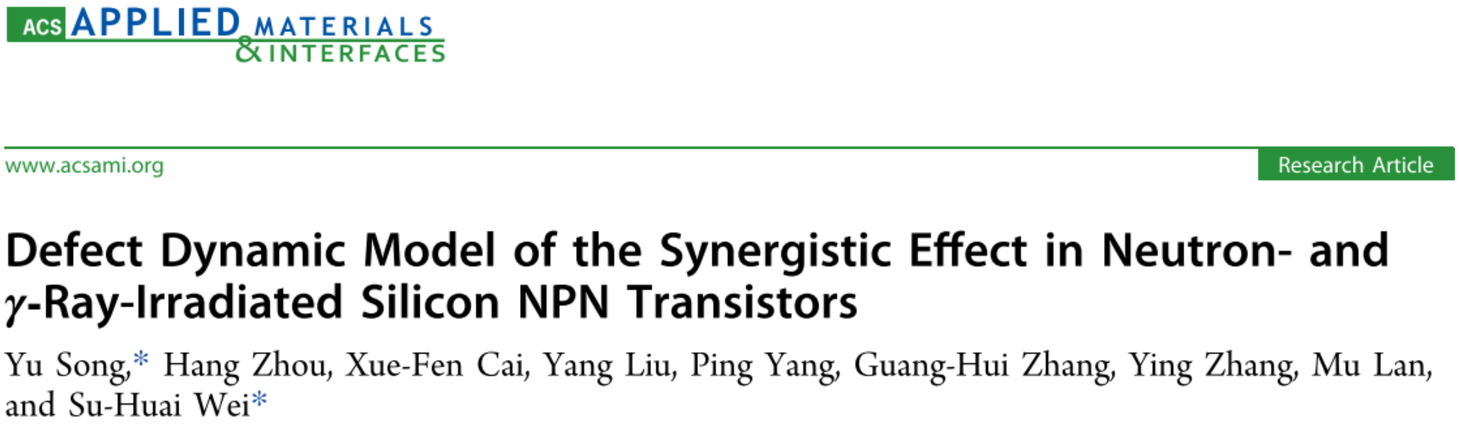
Su-Huai Wei†
Beijing Computational Science Research Center, Beijing 100193, China

(Dated: November 5, 2020)

The practical damage of silicon bipolar devices subjected to mixed ionization and displacement irradiations is usually evaluated by the sum of separated ionization and displacement damages. However, recent experiments show clear difference between the practical and summed damages, indicating significant irradiation synergistic effects (ISEs). Understanding the behaviors and mechanisms of ISEs is essential to predict the practical damages. In this work, we first make a brief review on the state of the art, critically emphasizing on the difficulty encountered in previous models to understand the dose rate dependence of the ISEs. We then introduce in detail our models explaining this basic phenomenon, which can be described as follows. Firstly, we show our experimental works on PNP and NPN transistors. A variable γ-ray dose and neutron fluence setup is adopted. Fluence dependent 'tick'-like and sublinear dose profiles are observed for PNP and NPN transistors, respectively. Secondly, we describe our theoretical investigations on the positive ISE in NPN transistors. We propose an atomistic model of transformation and annihilation of V_2 defects in p-type silicon under ionization irradiation, which is totally different from the traditional picture of Coulomb interaction of oxide trapped charges in silica on charge carriers in irradiated silicon. The predicted novel dose and fluence dependence are fully verified by the experimental data. Thirdly, the mechanism of the observed negative ISE in PNP transistors is investigated in a similar way as in the NPN transistor case. The difference is that in n-type silicon, VO defects also undergo an ionization-induced transformation and annihilation process. Our results show that, the evolution of displacement defects due to carrier-enhanced defect diffusion and reaction is the dominating mechanism of the ISEs. Finally, we give a perspective on future investigations on the ISEs when the displacement and ionization irradiations are present simultaneously.

Accepted by ACS AELM, spotlight on application.

新发展： Ionization-irradiation-induced evolution of displacement defects in Si



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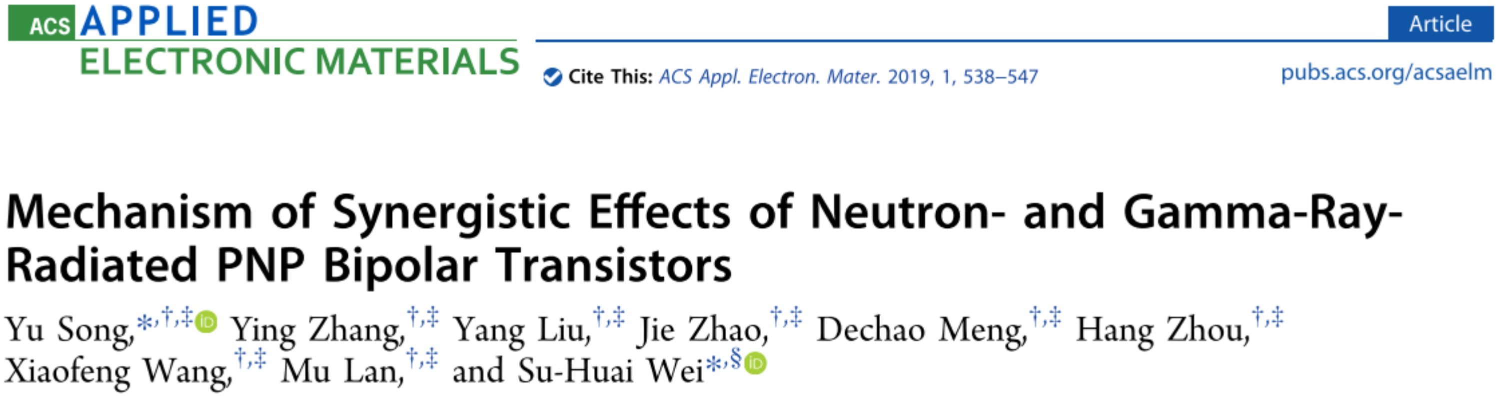
Research Article

Defect Dynamic Model of the Synergistic Effect in Neutron- and γ-Ray-Irradiated Silicon NPN Transistors

Yu Song,[*] Hang Zhou, Xue-Fen Cai, Yang Liu, Ping Yang, Guang-Hui Zhang, Ying Zhang, Mu Lan, and Su-Huai Wei[*]



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Article

Cite This: *ACS Appl. Electron. Mater.* 2019, 1, 538−547

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Mechanism of Synergistic Effects of Neutron- and Gamma-Ray-Radiated PNP Bipolar Transistors

Yu Song,[*,†,‡] Ying Zhang,[†,‡] Yang Liu,[†,‡] Jie Zhao,[†,‡] Dechao Meng,[†,‡] Hang Zhou,[†,‡] Xiaofeng Wang,[†,‡] Mu Lan,[†,‡] and Su-Huai Wei[*,§]

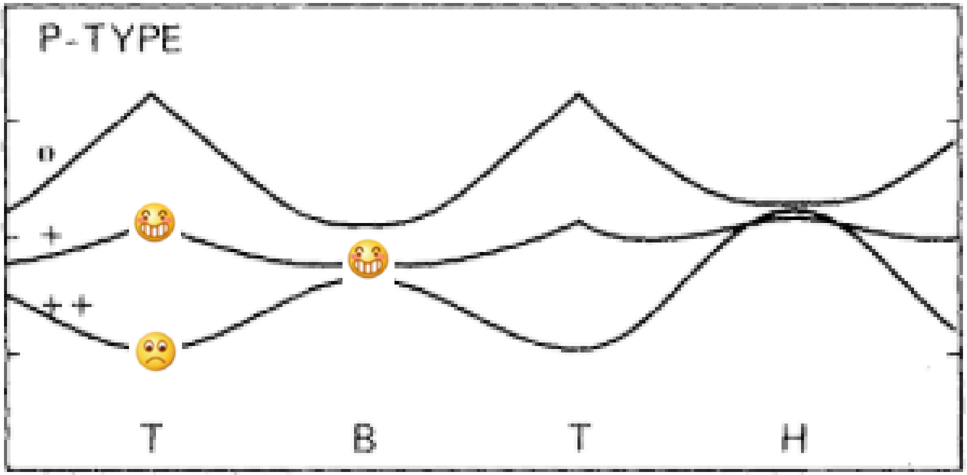
理论依据 1： 载流子增强的缺陷扩散

0、双极晶体管的基极电流大小正比于硅中位移缺陷的浓度

$$\Delta I_{iB}^{D} = \frac{q n_i A x_{dB}}{2\tau} e^{qV_{BE}/2k_B T}$$

τ^{-1}正比于缺陷浓度和载流子俘获截面

载流子增强的缺陷扩散（carrier-enhanced defect diffusion）

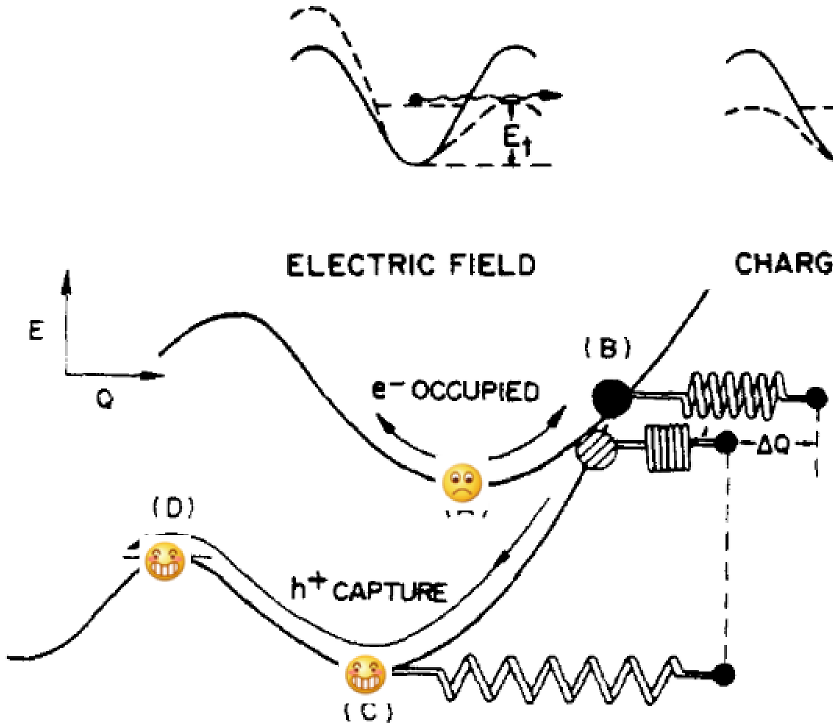


$$\begin{tikzcd}
I^{++}(T) \arrow[r, dashed] \arrow[d] & I^{++}(B) \\
I^{+}(T) \arrow[r] & I^{+}(B)
\end{tikzcd}$$

Car, R. Physical Review Letters 1984, 52, 1814.

理论依据 2：复合增强的缺陷反应

复合增强的缺陷反应
(recombination-enhanced defect reaction)



热能：$[E_t = E\ (\text{kinetic}) + E(B) - E(A)]$

电子能：$[E_R = E(A) - E(C)]$

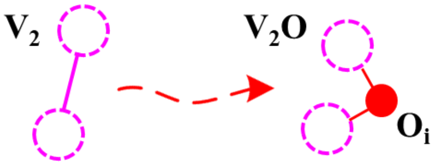
反应势垒：$[E_T = E(D) - E(C)]$

Kimerling, L. C. (1978). ***Solid State Electronics***, 21(11–12), 1391–1401

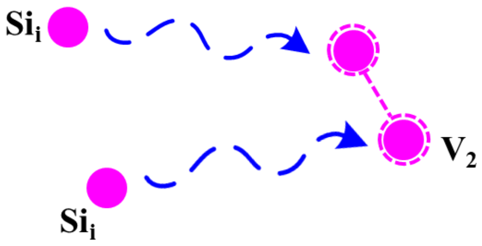
Lang, D. V., & Kimerling, L. C. (1974). Phys. Rev. Lett., 33(8), 489.

p型硅缺陷动力学模型

V2 扩散，被俘获



I 发射，与 V2 湮灭



- ✓ 缺陷演化

$$V_2 + O_i \rightarrow V_2O, \qquad (2a)$$

$$V_2 + 2Si_i \rightarrow 0. \qquad (2b)$$

- ✓ 速率方程

$$\partial V_2(t)/\partial t = -\kappa_1 V_2(t) - \kappa_2 F^2, \qquad (3a)$$

$$\partial V_2O(t)/\partial t = \kappa_1 V_2(t). \qquad (3b)$$

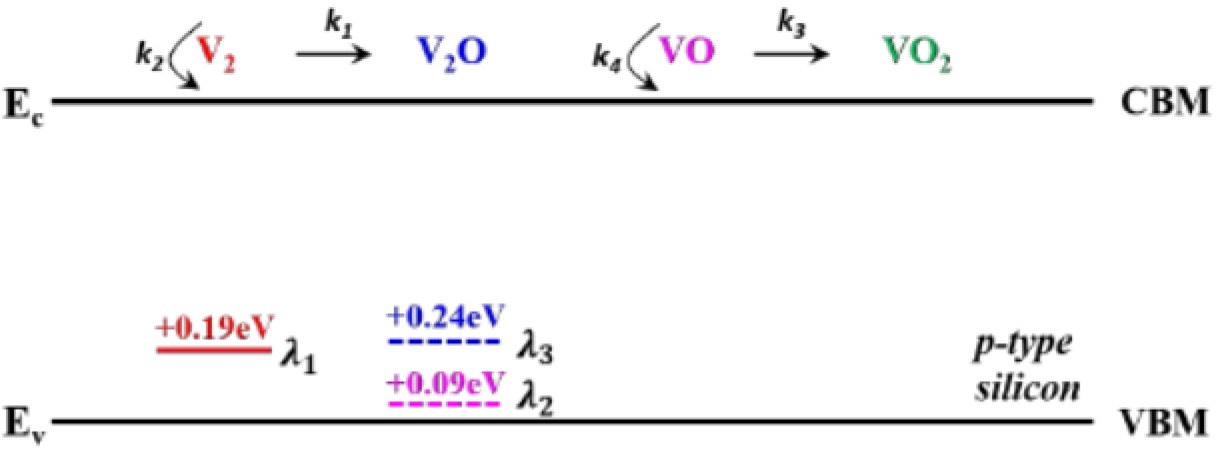
- ✓ 浓度函数

$$V_2(D) = (F + \kappa_1^{-1}\kappa_2 F^2)(e^{-\kappa_1 R^{-1} D} - 1) + F, \qquad (4a)$$

$$V_2O(D) = (F + \kappa_1^{-1}\kappa_2 F^2)(1 - e^{-\kappa_1 R^{-1} D}) - \kappa_2 F^2 R^{-1} D. \qquad (4b)$$

NPN晶体管电学响应模型

缺陷能级对器件电流的贡献因子：λ



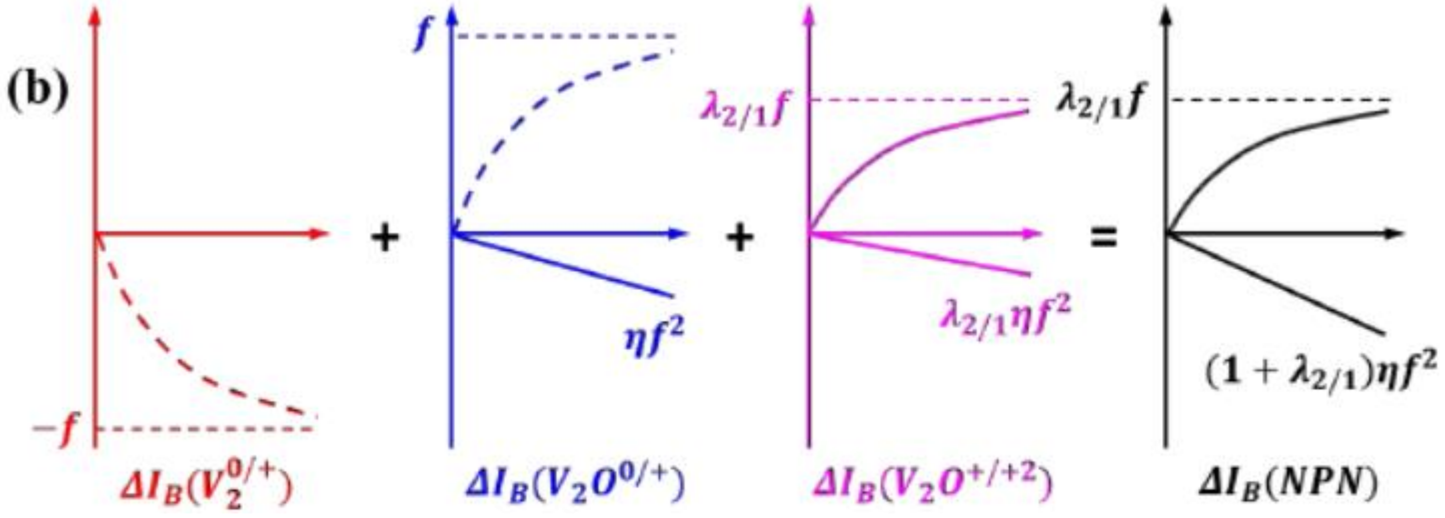
- ✓ 电流函数

$$\Delta I_B^{V_2^{0/+}}(D,f) = (f+\eta f^2)(e^{-D/\tau}-1), \qquad (6a)$$

$$\Delta I_B^{V_2O^{0/+}}(D,f) = (f+\eta f^2)(1-e^{-D/\tau}) - \eta f^2 D/\tau, \qquad (6b)$$

$$\Delta I_B^{V_2O^{+/+2}}(D,f) = \lambda_{21}\Delta I_B^{V_2O^{0/+}}(D,f). \qquad (6c)$$

NPN晶体管电学响应模型



✓ 协同效应

$$\Delta I_B(D,f)=\lambda_{21}(f+\eta f^2)(1-e^{-D/\tau})-(1+\lambda_{21})\eta f^2 D/\tau. \quad (7)$$

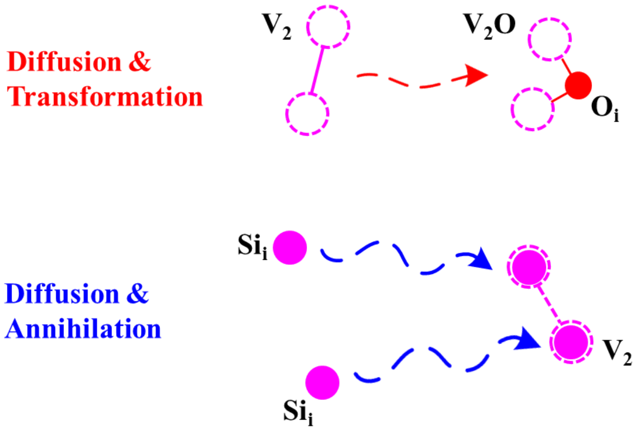
✓ 拟合公式

$$\Delta I_B^j=k_jD+A_j(1-e^{-D/\tau_j}), \quad (8)$$

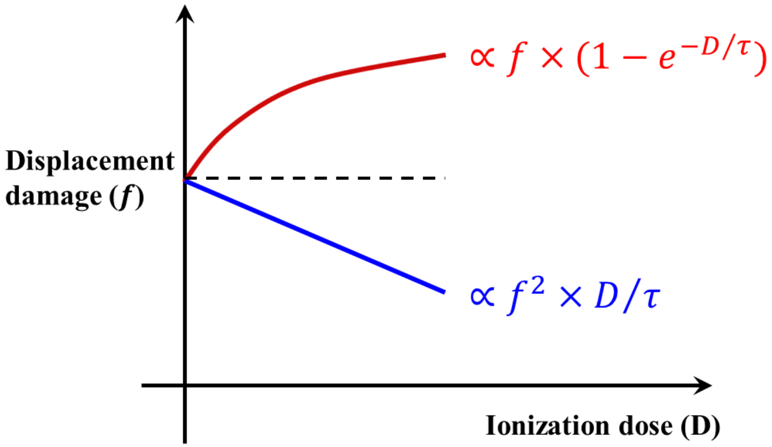
- ➢ 渐进增长项，其幅度正比于初始位移缺陷的一次方；
- ➢ 线性衰减项，其强度正比于初始位移损伤的二次方。

Big pictures for ISE in NPN & PNP transistors

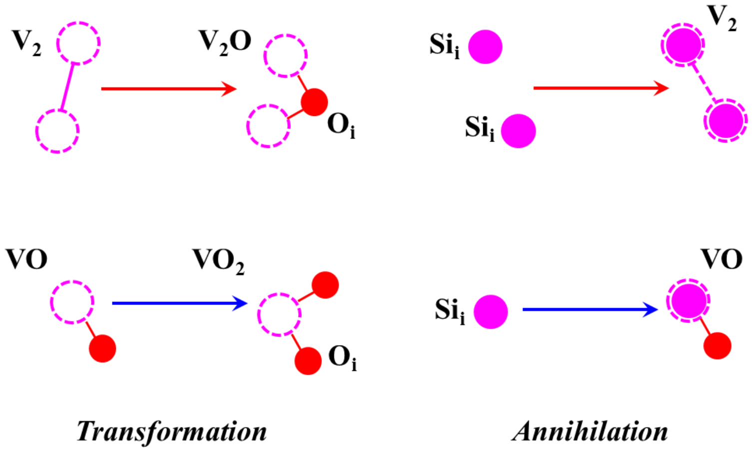
Defect dynamics in p-type silicon



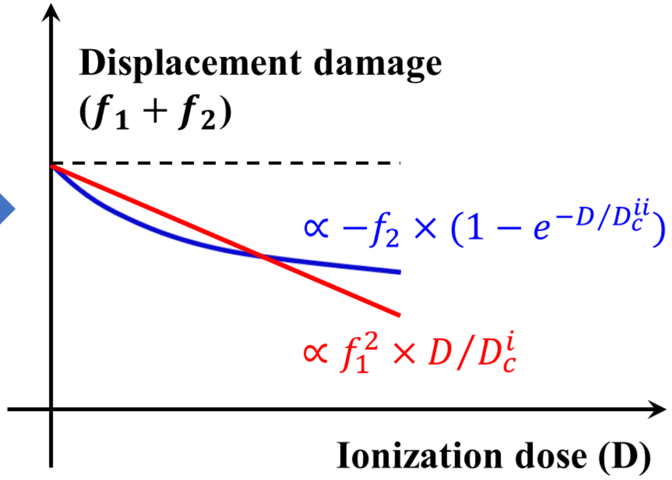
Base current of NPN transistor



Defect evolution in n-type silicon

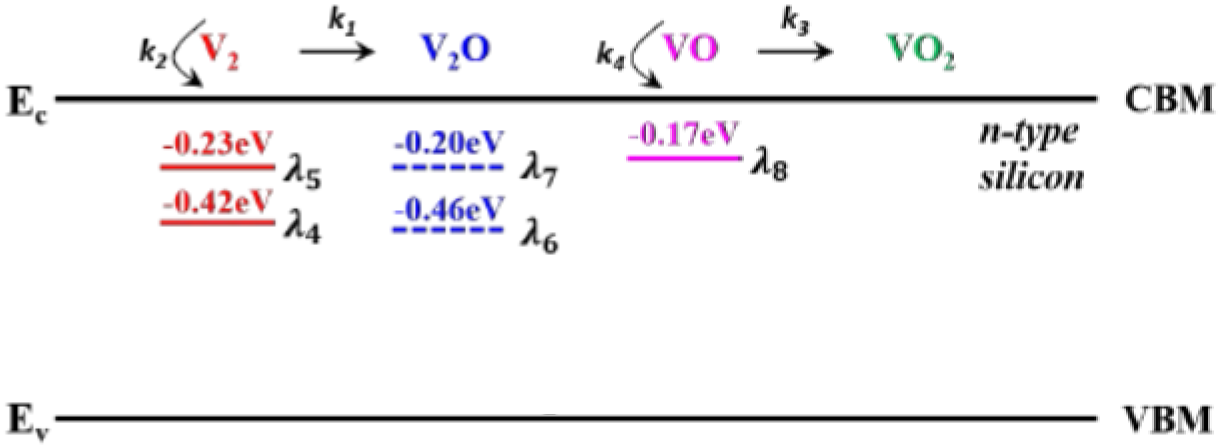


Base current of PNP transistor

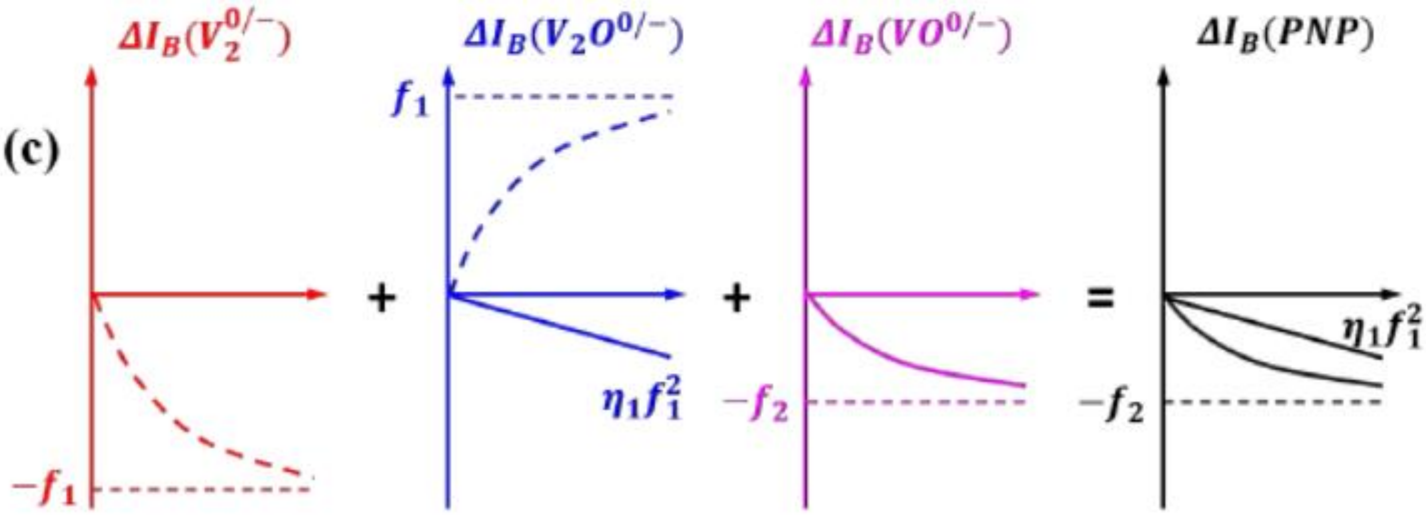


n-型硅中的缺陷演化和PNP中的电流

缺陷能级



电流分量

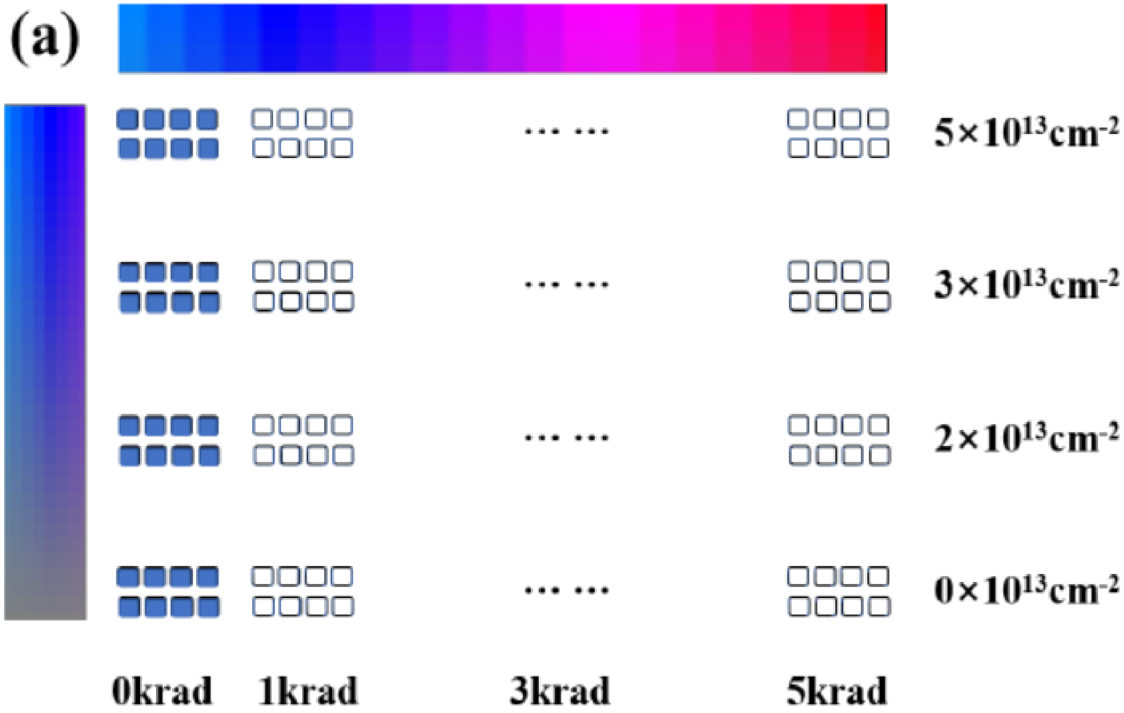


报告题纲

Part III: 硅基器件位移-电离辐照协同效应的机理

- ✓ 标准模型及存在问题
- ✓ 理论新发展
- ✓ 实验验证
- ✓ 研究展望

揭示协同效应规律的变剂量中子-γ射线辐照实验



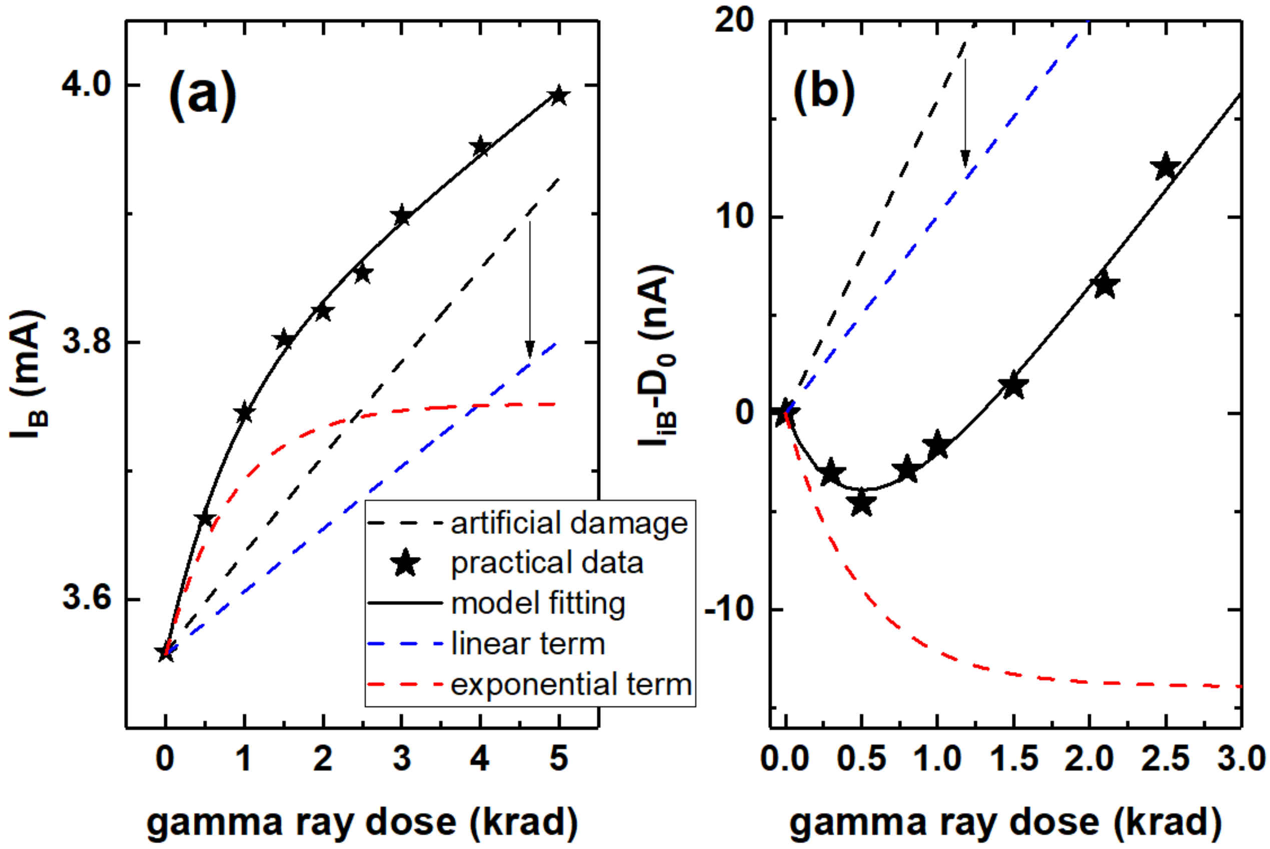
1、使用中子和γ射线辐射

2、顺序辐照构型

3、变剂量（剂量率）、变注量

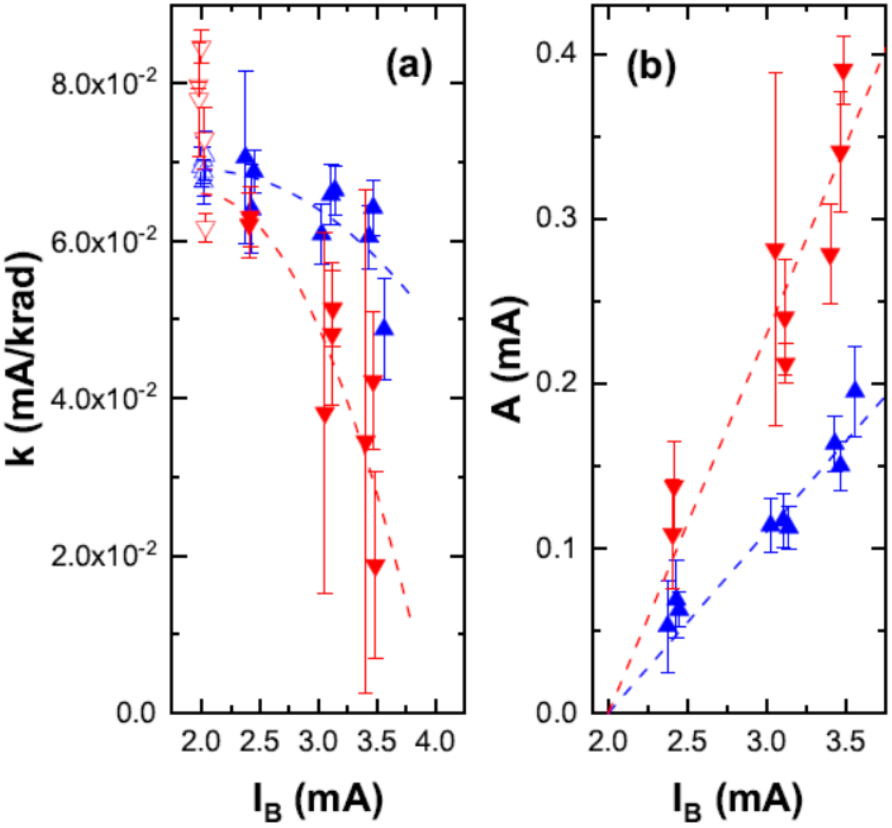
4、考虑样本间差异

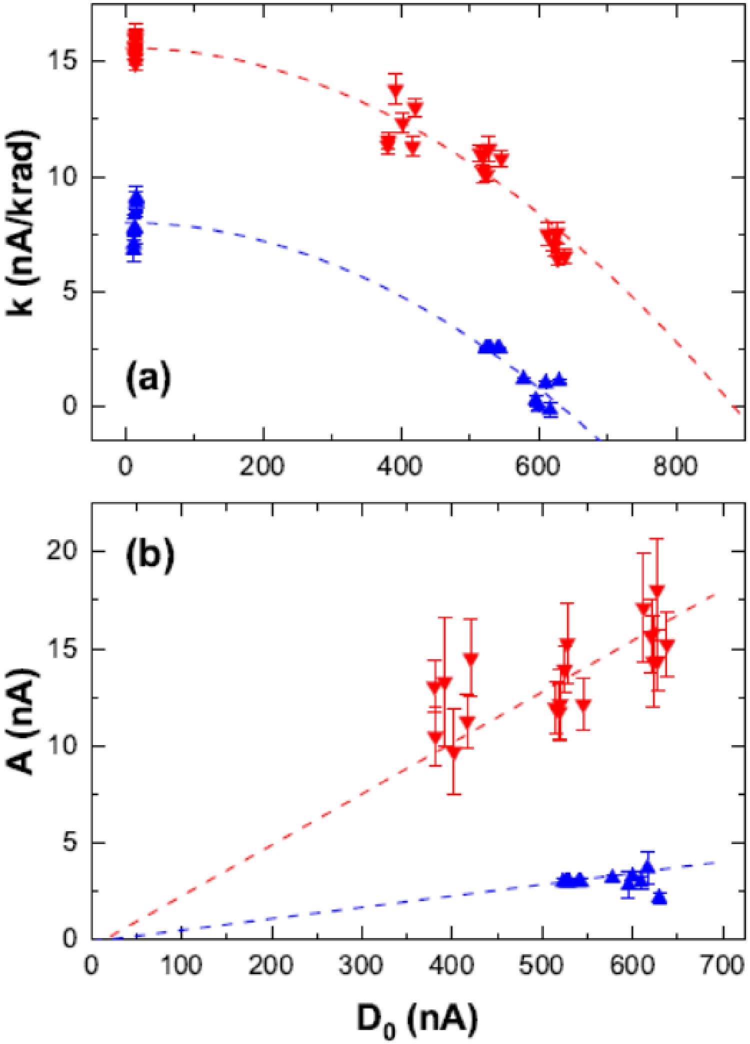
模型的实验验证——电离剂量依赖



两类晶体管的实验数据都可以通过对应的缺陷动力学模型定量拟合，且指数和线性分量与预期相符，证明模型对协同效应电离剂量依赖的预测正确

模型的实验验证—位移损伤依赖

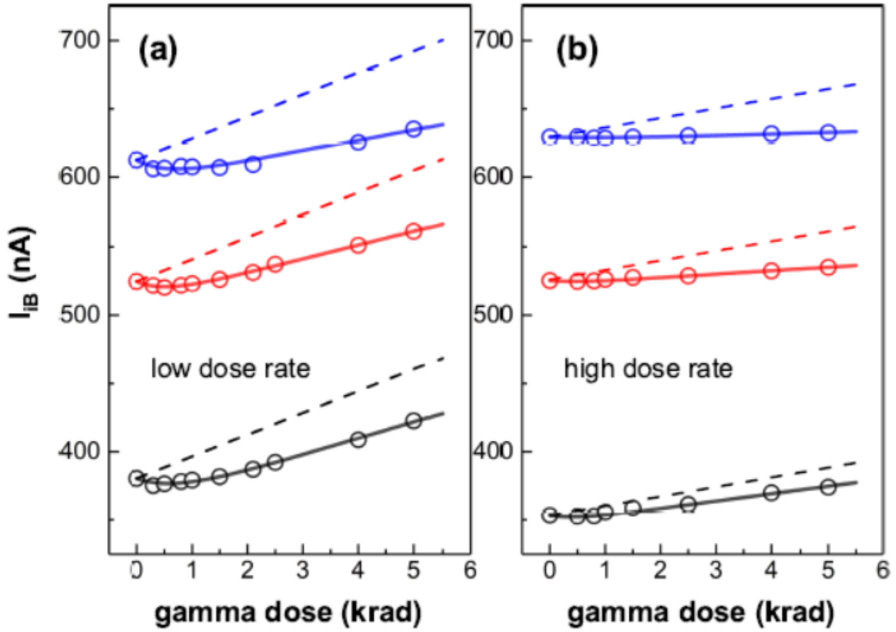


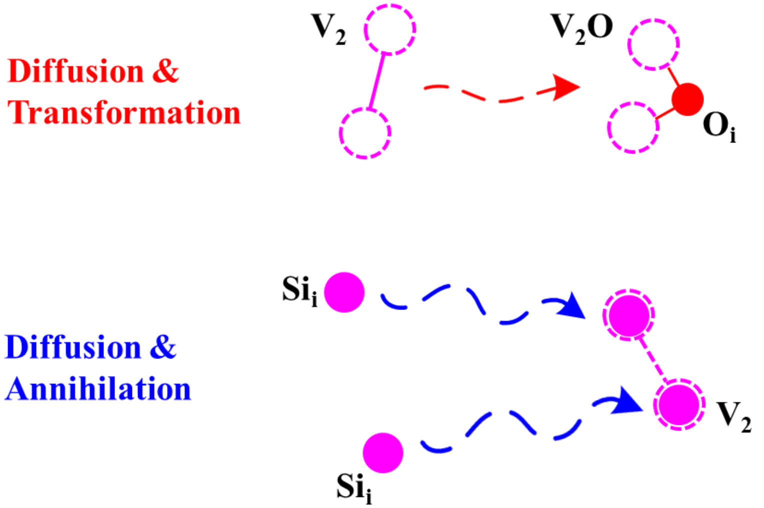


NPN（左）和PNP（右）晶体管协同效应中线性项的抽取参数二次方正比于初始位移损伤，指数项正比于初始位移损伤，均与理论预测相符。

红色和蓝色的差别：剂量率依赖

协同效应的剂量率依赖性





ISE剂量率依赖的机理

- ✓ 电荷增强缺陷扩散、复合增强缺陷反应均与剂量率相关
- ✓ 相同总剂量下，剂量率越低，协同效应越强

小结

新观点：硅中电离辐照诱导的位移缺陷演化

- ✓ 自洽、统一地解释npn、pnp晶体管协同效应对电离剂量的依赖性
- ✓ 由于电活性缺陷及其转化产物不同， npn、pnp晶体管表现出完全不同的电离剂量依赖行为
- ✓ 自洽解释初始位移损伤依赖性
- ✓ 自洽解释以往不能解释的剂量率依赖性

报告题纲

Part III: 硅基器件位移-电离辐照协同效应的机理

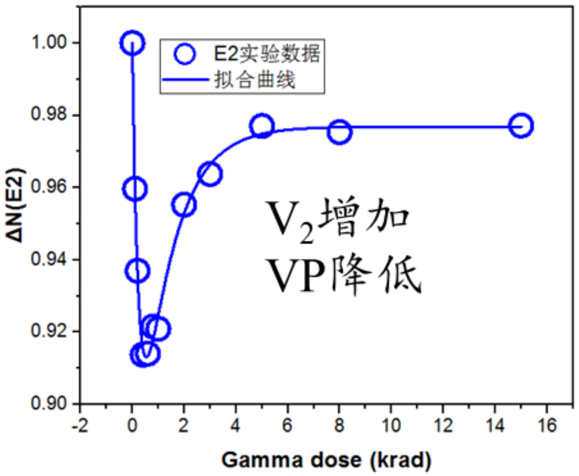
✓ 标准模型及存在问题
✓ 理论新发展
✓ 实验验证
✓ 研究展望

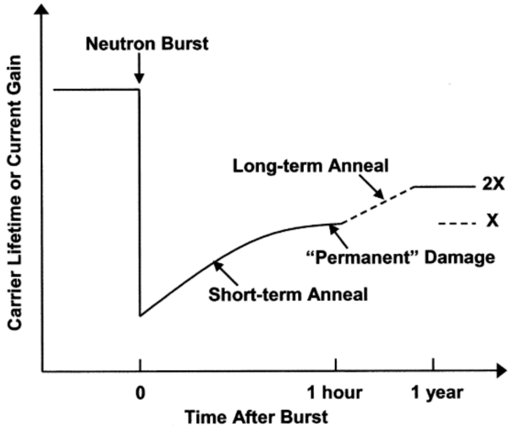
研究展望

1、位移缺陷演化的DLTS表征，提供缺陷演化机理的直接实验证据

2、辐射协同效应的剂量率依赖特性及机理，进一步挖掘载流子增强缺陷扩散、复合增强缺陷反应的属性

3、电离对位移损伤快速产生、早期退火过程的协同作用，位移和电离辐射同时作用时协同效应的行为特征和机理





报告小结

- 半导体辐照效应机理研究具有重要的工程应用价值和学术研究价值
- 本报告重点介绍了硅基材料中辐照诱导缺陷动力学的研究现状和新近发展
- 以往认为该领域已经很成熟了，只是修修补补的工作
- 我们认为完全没有，还有很多基本的概念需要发展
- 在这些基石上，整个领域的大厦可能需要重构

Thank You for Your Attention !