RASER中LGAD探测器的仿真

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代表RASER团队*

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RASER

raser 3.2.0

```
pip install raser
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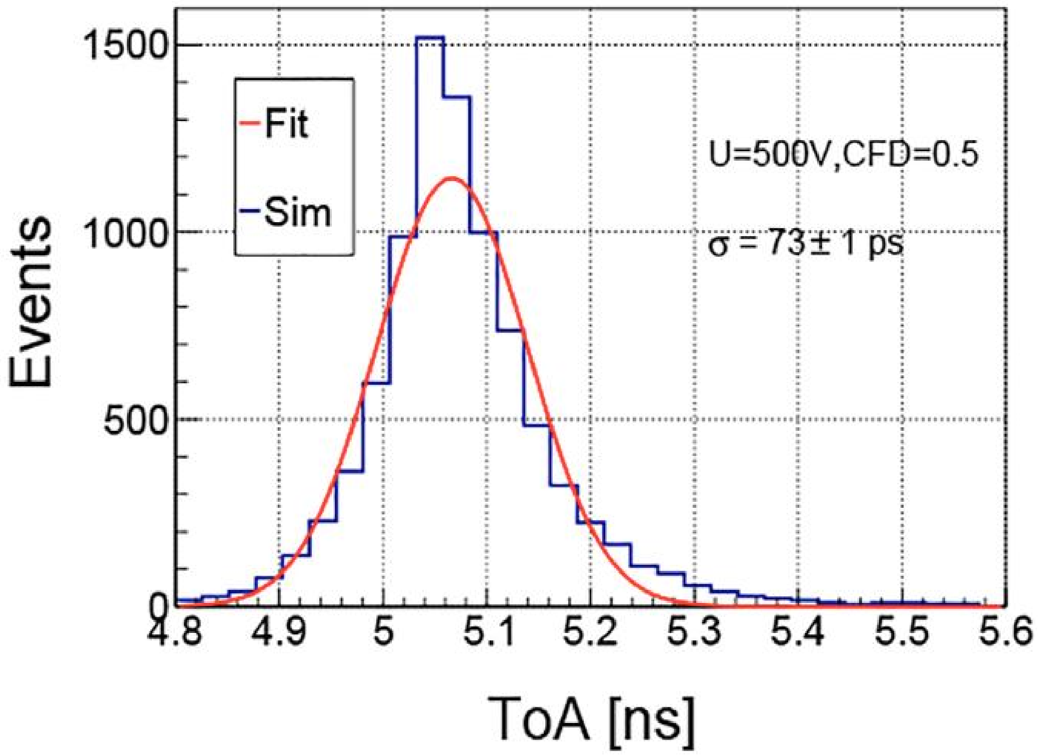
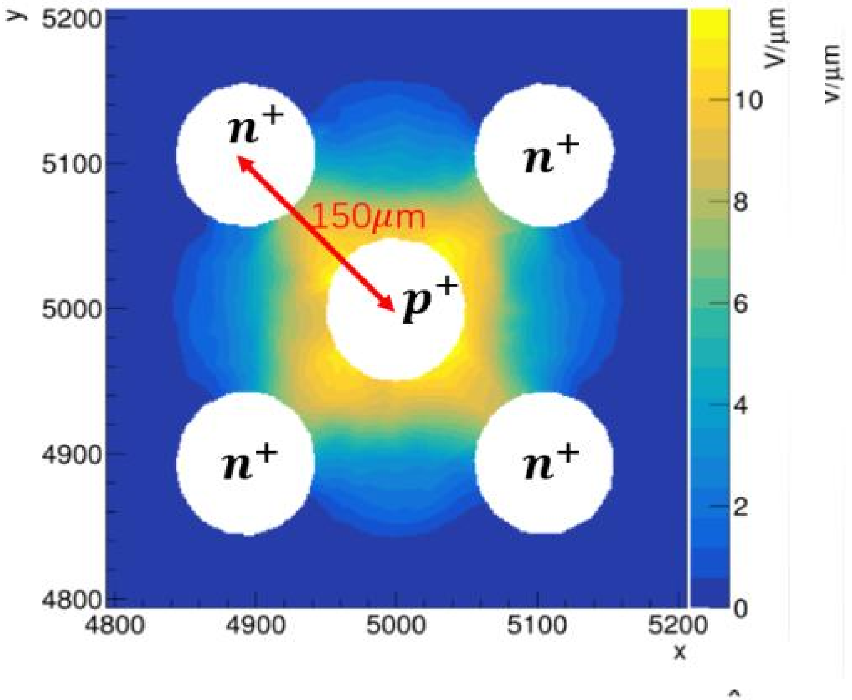
- RASER=RAdiation SEmiconductoR
- RASER TEAM开发（高能所、吉大、山东高研院等）
- 基于PYTHON开发
  - GEANT4、DEVSIM、FENICS、ROOT
- 目标：预测碳化硅探测器的时间分辨性能
  - 3D、PIN、Microstrip
  - LGAD Edge-TCT

已发表成果

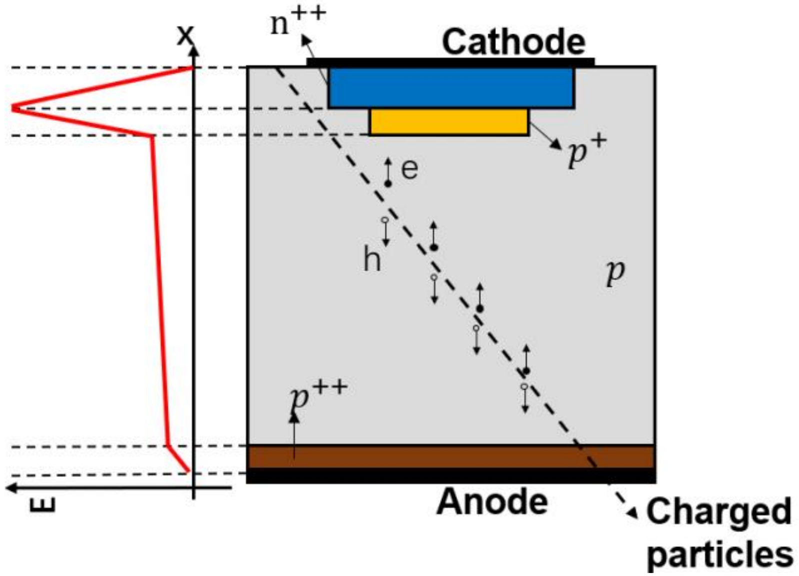


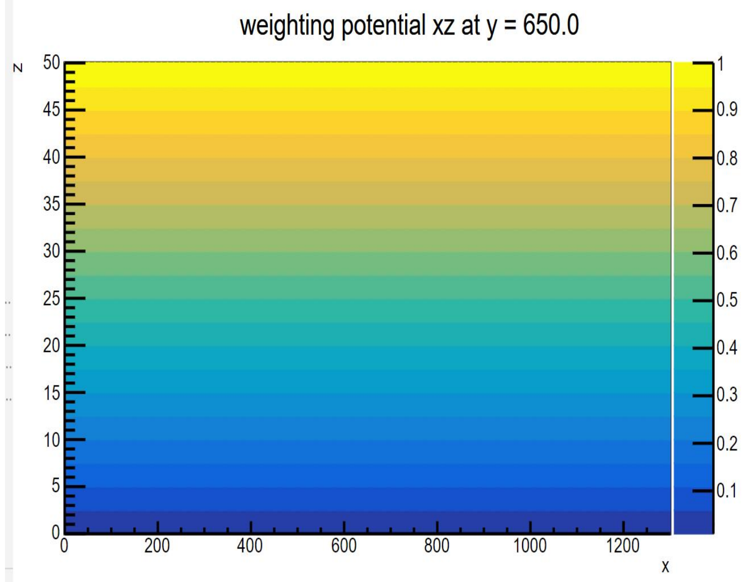
NJU 5mm × 5mm 4H-SiC-PIN的时间分辨
RASER仿真结果为73±1ps，实验测得94±1ps
[Front. Phys. 10:718071.](#)



预测4H-SiC 3D结构探测器的时间分辨
可达到25ps
[Micromachines 2022,13,46.](#)

HPK 3.1-50 LGAD





平面型结构：

$50\ \mu m$ & $1.3 \times 1.3\ mm^2$

p区掺杂$1.0 \times 10^{12}\,cm^{-3}$

增益区:

$$p+\begin{cases}1.0\times10^{12}cm^{-3},\ 0\mu m<z<1\mu m\\1.913\times10^{18}cm^{-3},\ 1\mu m<z<2\mu m\end{cases}$$

增益~24倍，耗尽电压约45V

电场方程:$\nabla^2 U(x) = -eN_{eff}/\varepsilon$

- 仅考虑空间电荷区
- 全耗尽

加权场方程: $\nabla^2 U_w = 0$

边界条件：$U_w = 1$ 读出电极

$U_w = 0$ 非读出电极

平面型探测器$E_w \sim 1/d$

增益模型

- **电离率: van Overstraeten模型**

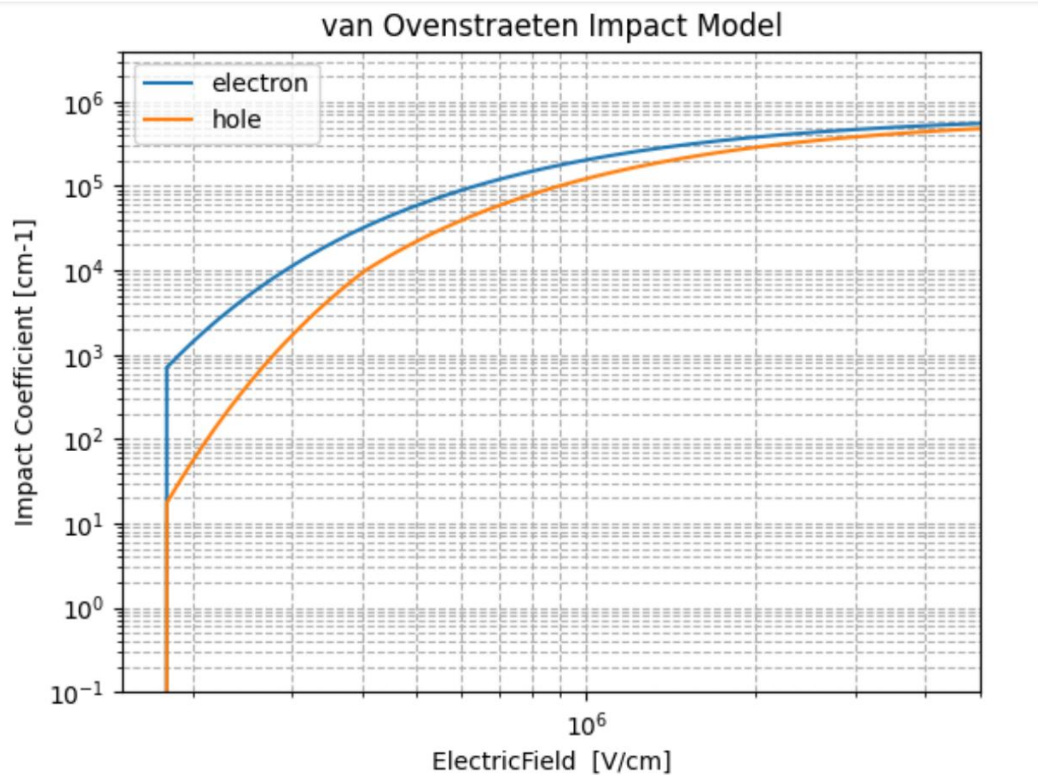
$$\alpha_{p,n}(T;E)=\frac{tanh(\hbar\omega/2k_{T_0})}{tanh(\hbar\omega T_0/2k_{T_0}T)}a_{p,n}exp(-b_{p,n}/E)$$

$$a_n=7.03\times10^5cm^{-1},b_n=1.231\times10^6V\cdot cm^{-1},$$
$$a_p=1.582\times10^6cm^{-1},b_p=2.036\times10^6V\cdot cm^{-1}$$

- **增益系数**

$$M(x)=\frac{exp[\int_0^x(\alpha_n-\alpha_p)dx]}{1-\int_0^W\alpha_p exp[\int_0^x\alpha_n-\alpha_p dx]dx}$$

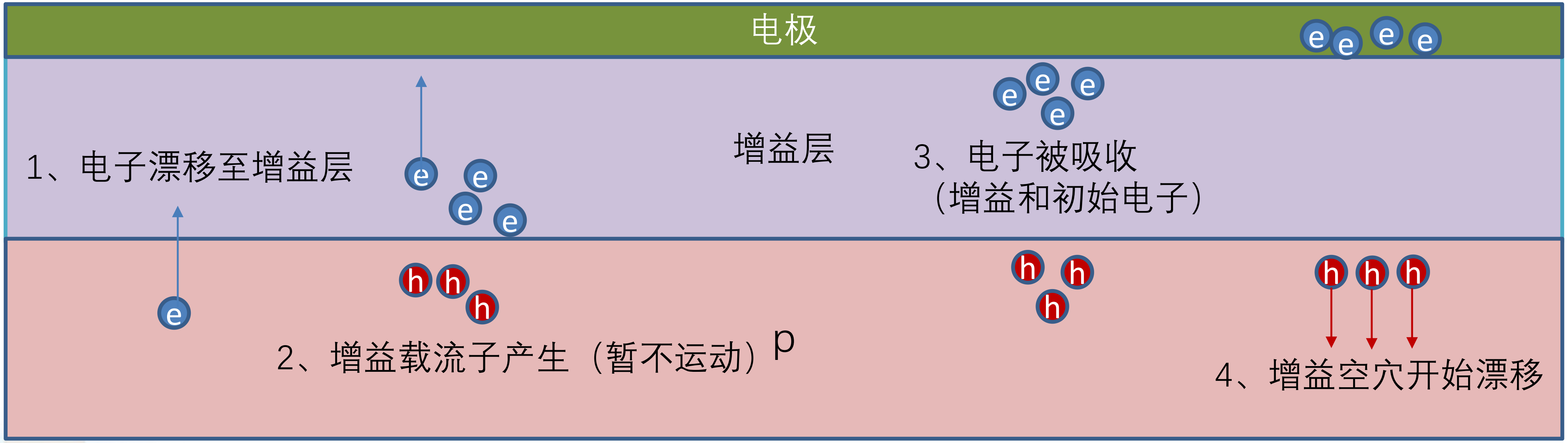
增益倍数$M=M(d_{gain})$



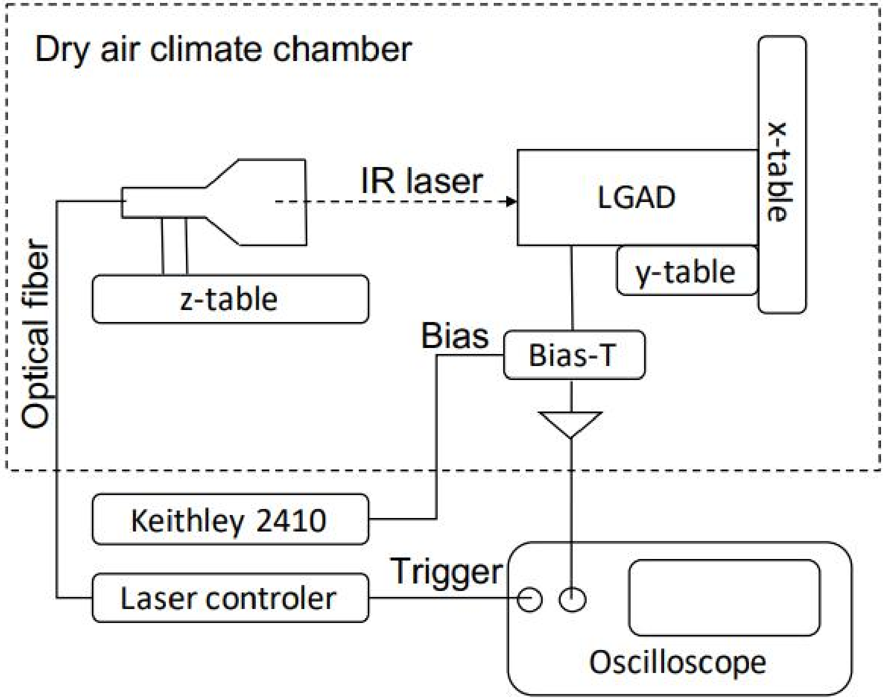
硅中的电离率模型， $E<1.75\times10^4\ V/m$ 时忽略电离

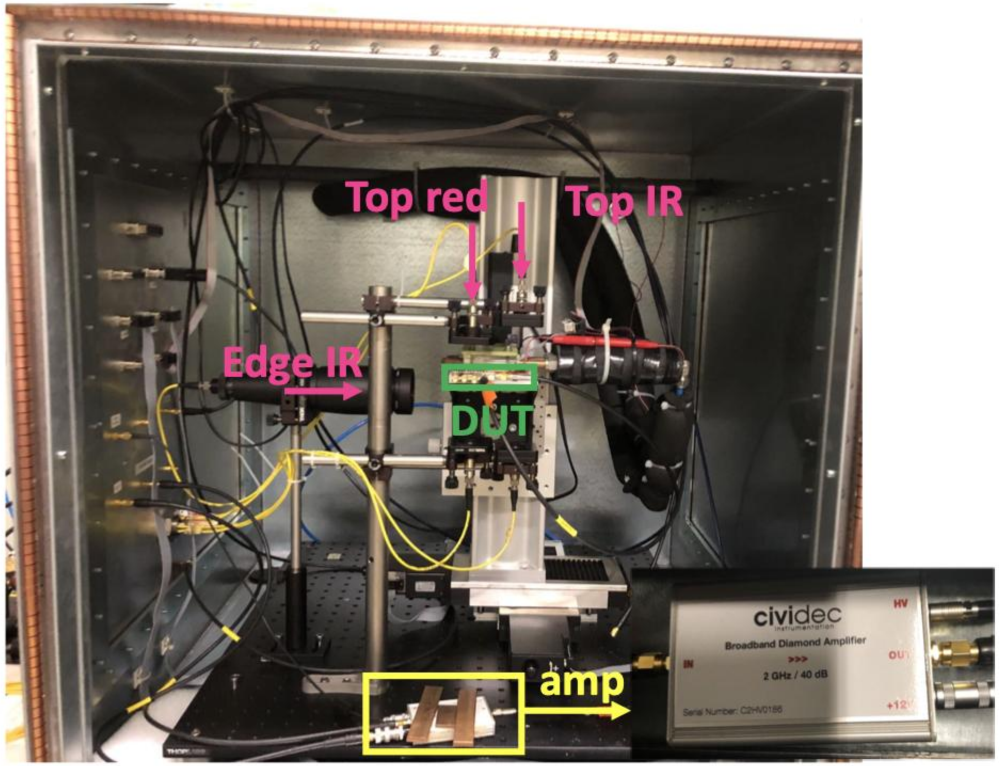
增益模型

- 1个电子在增益区产生M对增益载流子
- 当电子被吸收时释放增益空穴
- 增益电子瞬间被电极吸收
- 增益空穴漂移产生增益信号



Edge-TCT实验





CERN RD50 Group, 2019
激光：波长1064nm，束腰半高宽8μm，展宽350ps
X,Y,Z三轴步进机，步长1μm

信号收集&电子学

感应电流由肖克利-拉莫定理计算

$$I_q(t) = q\overrightarrow{v_q}(t)\cdot\nabla U_w(\overrightarrow{v_q}(t))$$

$$I_q(t)dt = q\overrightarrow{v_q}\nabla U_w dt = q\frac{d\overrightarrow{x_q}}{dt}\frac{dU_w}{dx} = qdU_w(\overrightarrow{x_q})$$

$$\bar{I}_{(t_1,t_2)} = \sum_q \sum_{t\epsilon(t_1,t_2)} I_q(t)dt$$

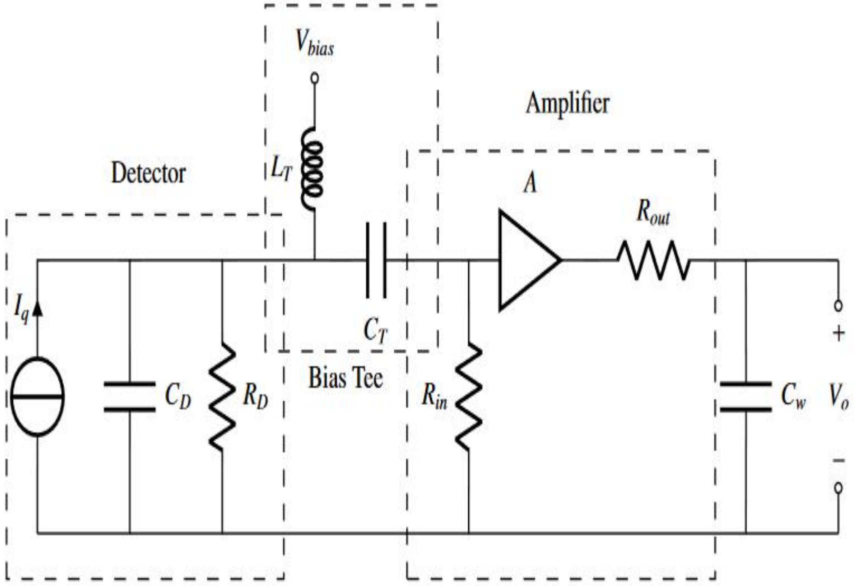
读出电路传递函数

$$h(t) = A'\cdot\frac{exp(-t/\tau_{RC_D}) - exp(-t/\tau_{RC_w})}{\tau_{RC_D} - \tau_{RC_w}}$$

$$A' = A\cdot\frac{\tau_{RC_D}}{C_D}, \tau_{RC_D} = R_{in}C_TC_D/(C_T + C_D), \tau_{RC_w} = R_{out}C_w$$

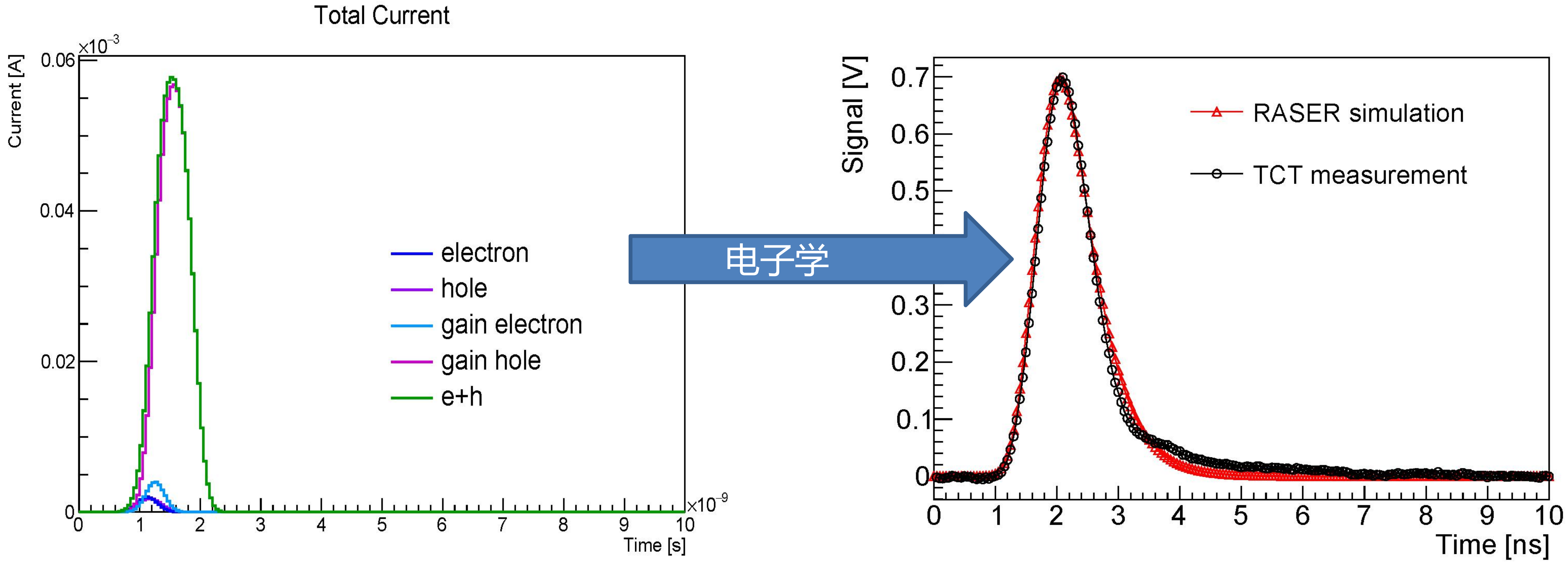
读出电压(V)

$$v_{out}(t) = i_{in}(t) * h(t)$$



实验读出电路

TCT LGAD仿真波形

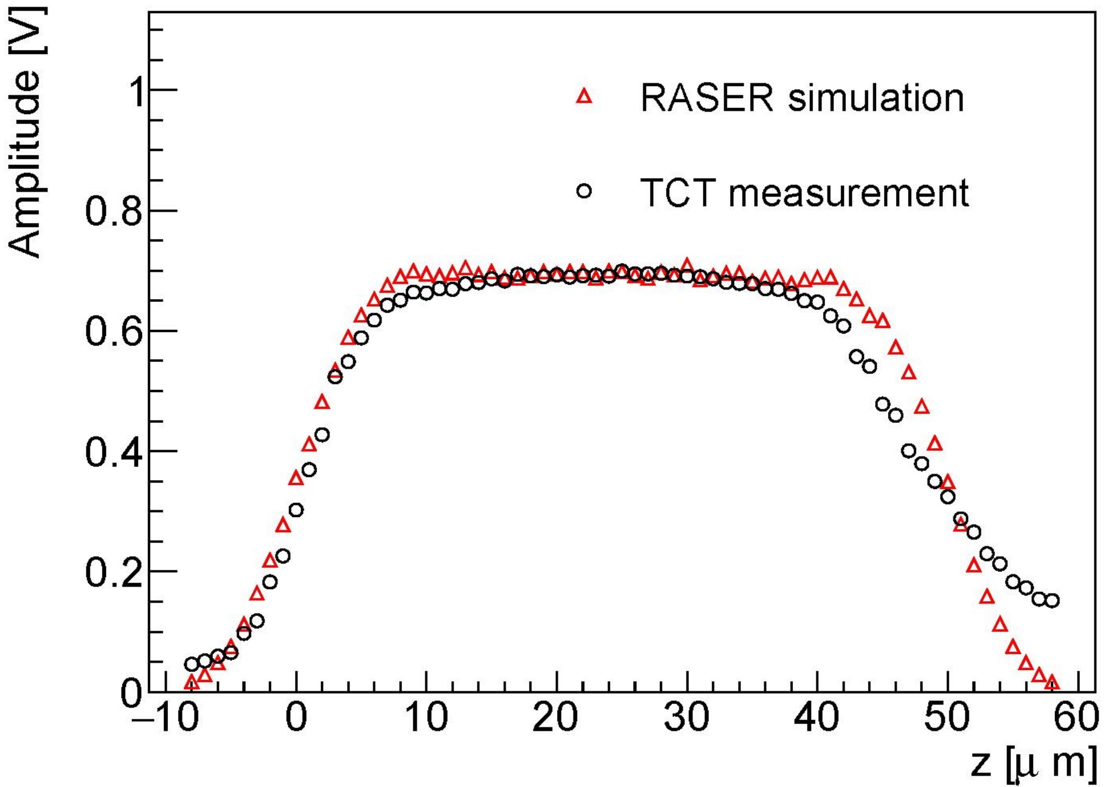


仿真载流子信号贡献图

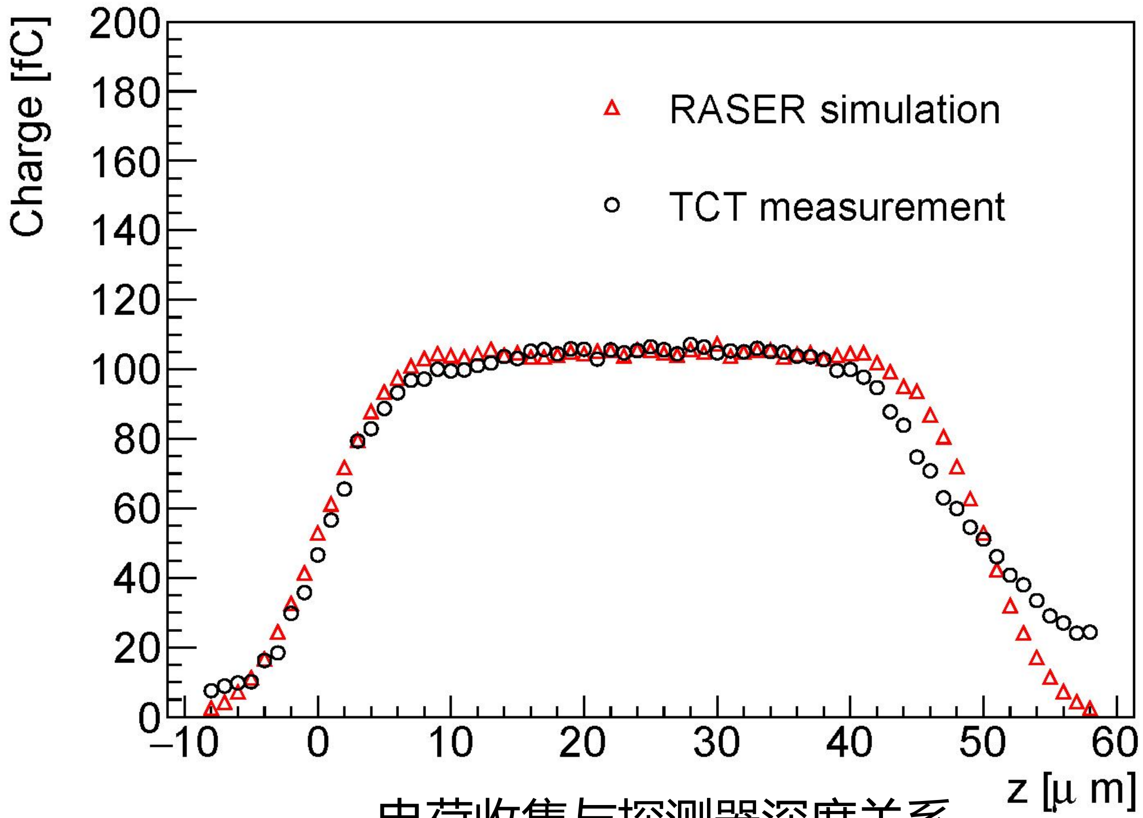
实验（黑）-仿真（红）波形对比

- 实验和仿真波形符合良好
- 增益空穴贡献了大部分信号
- 增益信号和原始信号难以区分

幅值&电荷收集



信号幅值与探测器深度关系



电荷收集与探测器深度关系

- 实验与仿真结果大致符合
- 靠近探测器底部差异由衬底中掺杂和激光在衬底产生的载流子导致

速度剖面(Velocity Profile)

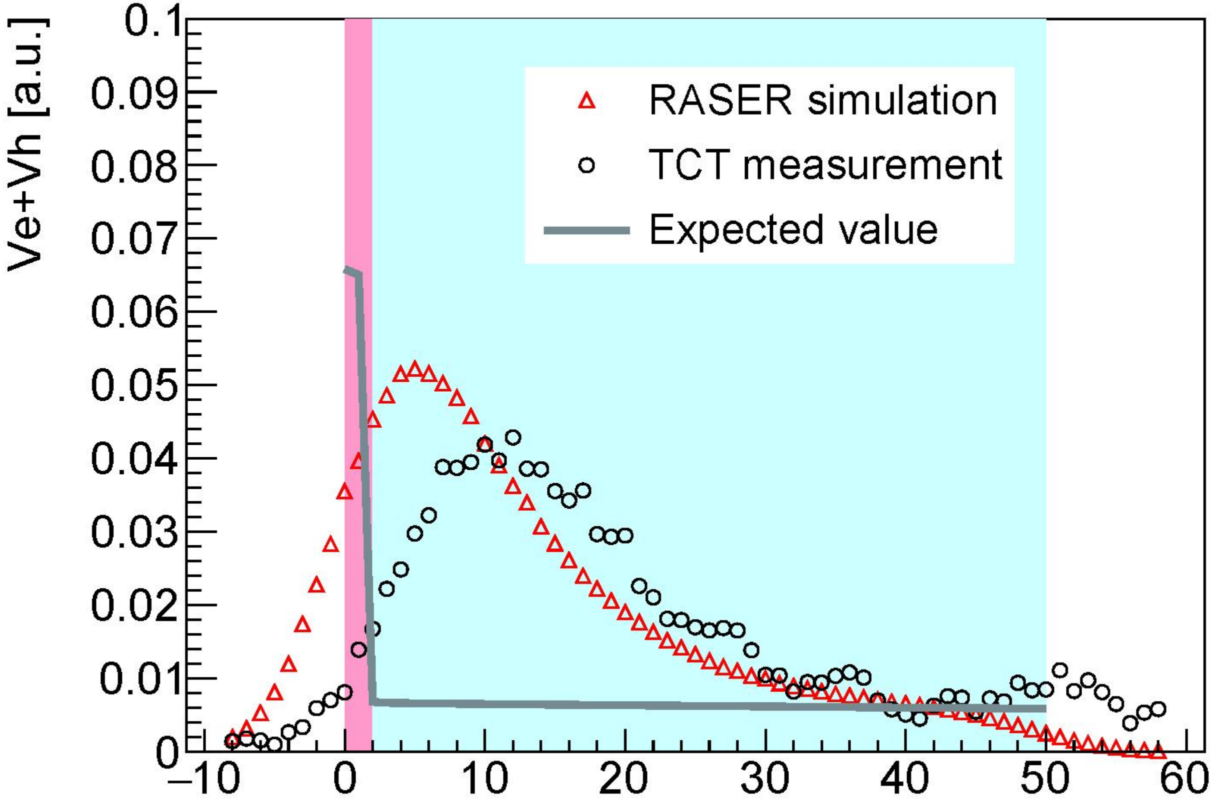
在特定位置z_0处产生一对载流子，产生后瞬间的速度和为:

$$
\begin{aligned}
&v_e(t)+v_h(t)\\
&=\mu_e[E(z_e)]E(z_e)+\mu_h[E(z_h)]E(z_h)\\
&\approx\{\mu_e[E(z_0)]+\mu_h[E(z_0)]\}E(z_0)
\end{aligned}
$$

产生的感应信号:

$$
I_q(z;t\to t_0)=\sum_q q\overrightarrow{v_q}(t)\nabla U_w
$$

$$
\approx\frac{ne}{d}(\mu_e+\mu_h)E(z)
$$



(V_e+V_h) − 深度的关系，蓝色区域为探测器区域，粉色为增益层

仿真z = 5μm，实验z = 10μm出现峰值，与已知的LGAD内部电场不符

扩散剖面(Diffusion Profile)

除定向漂移外的随机运动引入Langevin项

$$\Delta\vec{x}_{Langevin} \sim N(0,2Dt), D = \frac{k_B T\mu}{q}$$

- **非平衡载流子在电场中漂移和扩散满足高斯分布**

$$N = \boxed{N_0 \frac{1}{\sqrt{2\pi\tau^2}} exp(-\frac{t^2}{2\tau^2}) \frac{1}{\sqrt{2\pi\sigma_0^2}} exp(-\frac{z^2}{2\sigma_0^2})} * \boxed{\frac{1}{\sqrt{2\pi\sigma_D^2}} exp(-\frac{(z-\mu E t)^2}{2\sigma_D^2})}$$

高斯光束

漂移和扩散

- **载流子在增益层发生“反射”，“反射”产生满足相同分布的增益空穴** $dN \rightarrow MdN$

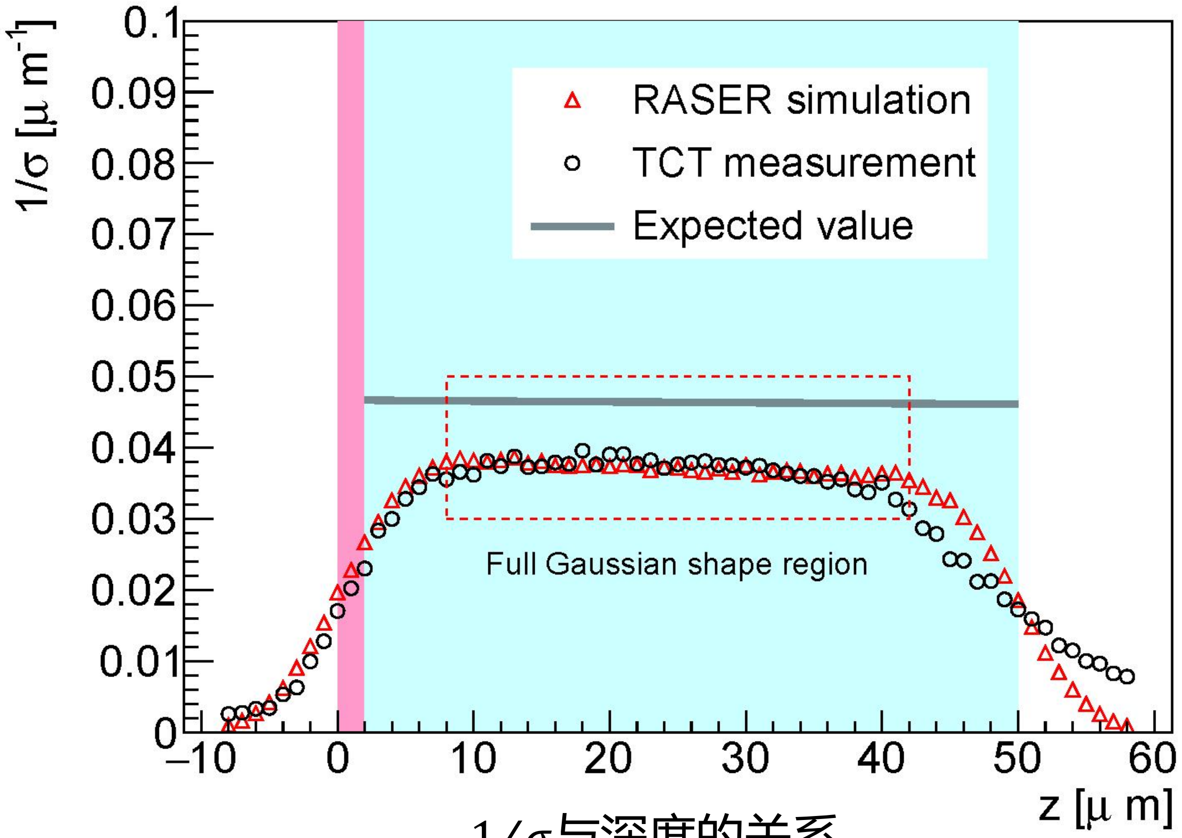
- **增益空穴开始漂移，由S-R定理感应电流信号**$I_q \propto MdNv_e' q/d$**，信号上升最快处对应光激发载流子团的中心**

$$(\frac{dI_q}{dt})_{max} = \frac{k_2 E_p}{\sigma_{eff}(z)}$$

k_2由激光和探测器性质决定、E_p为激光脉冲能量

$$\frac{1}{\sigma_{eff}(z)} = \int_0^{x_{max}} \frac{exp(-\alpha x)\alpha dx}{\sqrt{\tau^2 v_e^2 + \frac{E_e^2}{E_i^2}[\frac{\omega_0^2(x)}{4} + \frac{k_1}{2}(1 - \frac{E_i^2}{E_e^2})]}}$$

扩散剖面(Diffusion Profile)



$1/\sigma$与深度的关系

$$\frac{1}{\sigma_{eff}(z)}=\int_0^{x_{max}}\frac{exp(-\alpha x)\alpha dx}{\sqrt{\tau^2 v_e^2+\frac{E_e^2}{E_i^2}[\frac{\omega_0^2(x)}{4}+\frac{k_1}{2}(1-\frac{E_i^2}{E_e^2})]}}$$

$\tau v_e=15\mu m,\frac{E(z_e)}{E(z)}<1.1$，结果约为一个常数

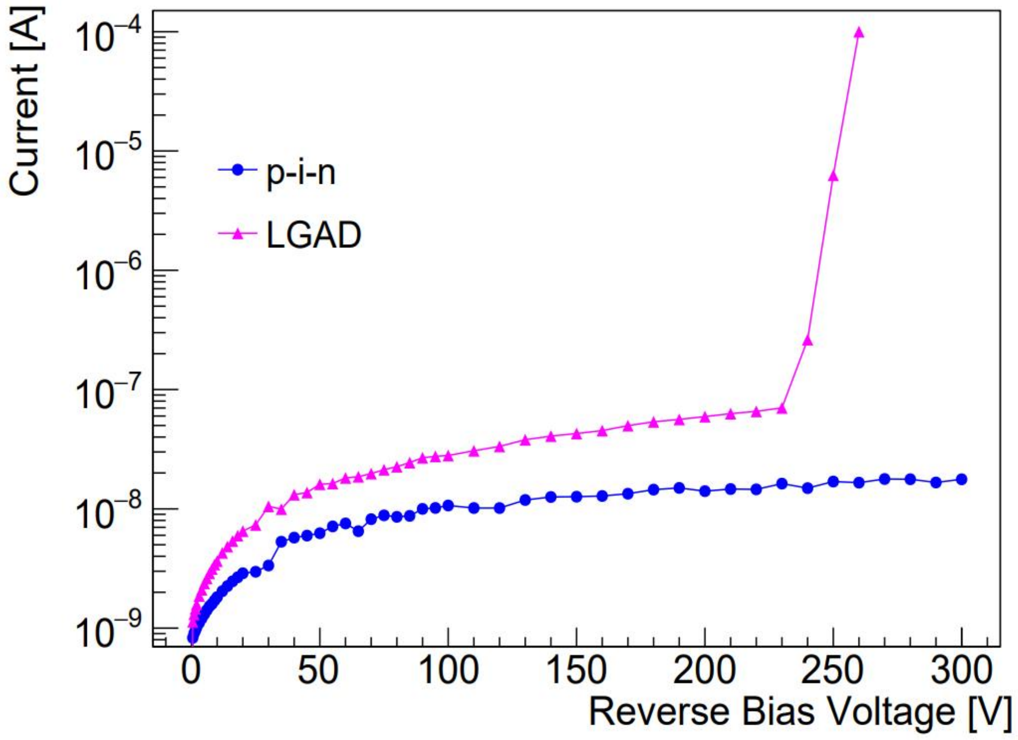
如果τv_e更小，则将会得到更多信息

总结

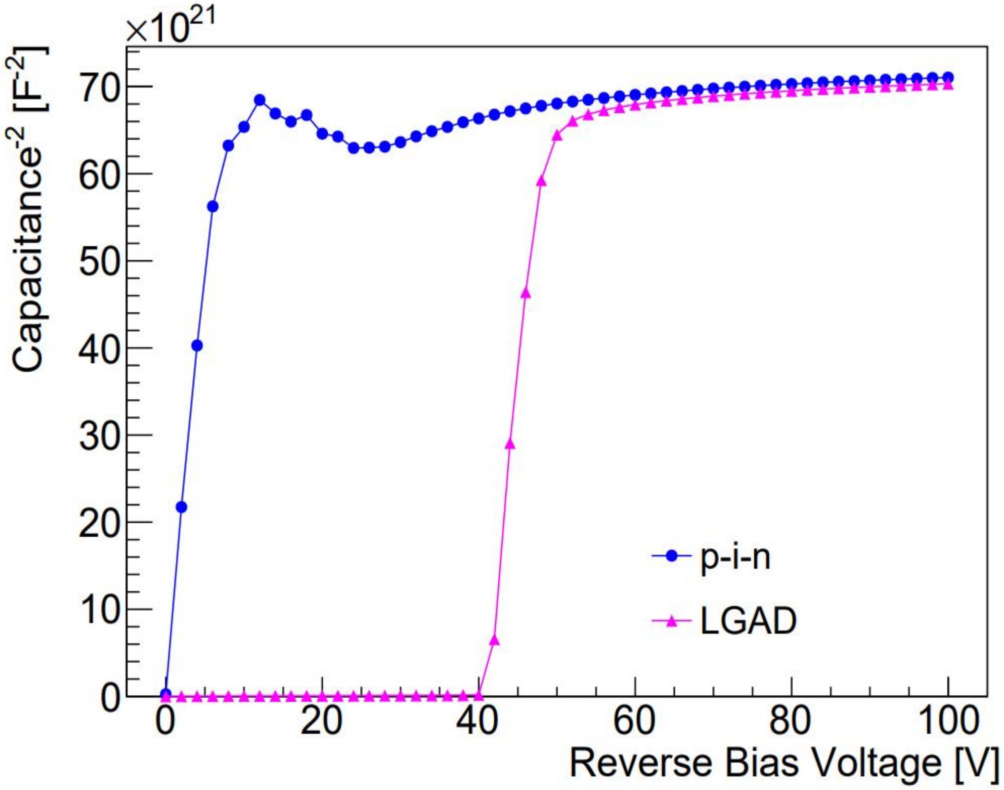
- 提出并检验了模拟增益过程的一种简化方法
- 在RASER中实现了对硅LGAD探测器的仿真并与实验结果相一致
- 提出了扩散法（Diffusion Profile Method）探测LGAD探测器的电场信息
- 未来目标：
    - 辐照后探测器
    - SiC PIN&LGAD

谢谢！

附录：I-V&C-V



I-V测试曲线(蓝) PIN (红) LGAD



C-V测试曲线(蓝) PIN (红) LGAD

击穿电压约220V，耗尽电压约为45V

附录：激光

Light intensity of Gaussian beam:

$$I(r,z;t) = I(0,0;0)\frac{w_0}{w(z)}\exp\frac{-2r^2}{w^2(z)}\exp\frac{-4t^2\ln 2}{\tau^2}$$

$$w(z) = w_0\sqrt{1+(2z/L)^2}$$

$$\lambda = 1064\mathrm{nm}, w_0 = 8\mu\mathrm{m}, \tau = 350\mathrm{ps}$$

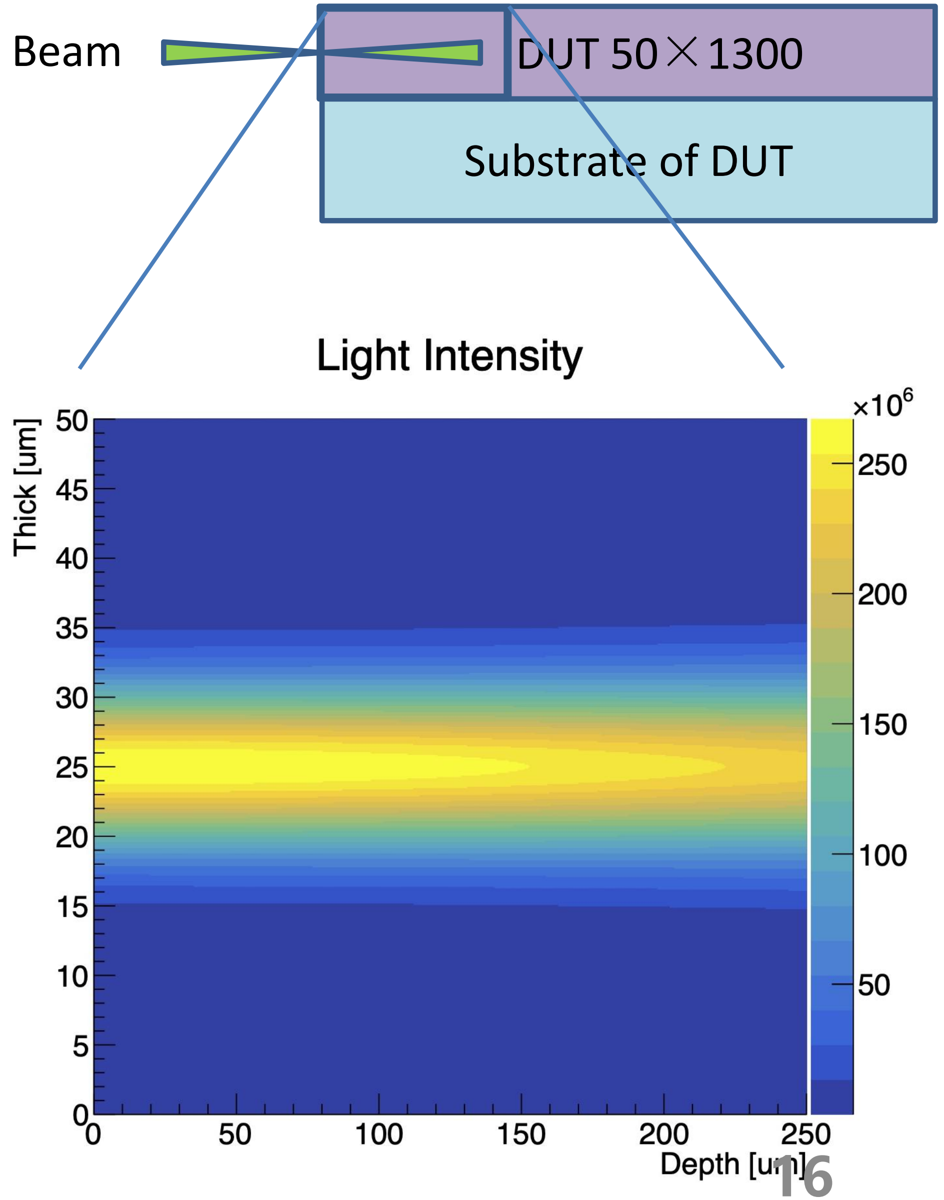
Absorption & refraction :

$$I'(r,z';t) = I_0(r,z;t)\exp(-\alpha(\lambda)z'), z' \approx nz$$

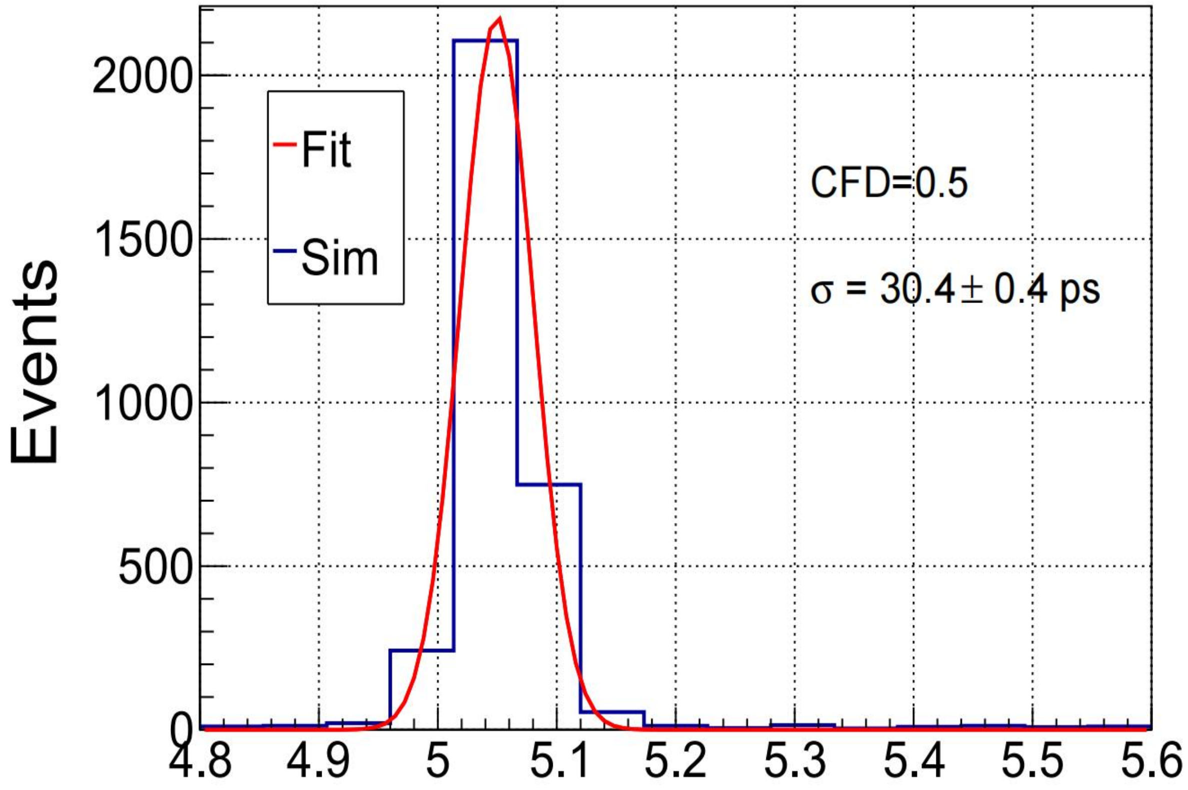
$$\alpha(1064\mathrm{nm}) = 9.87\mathrm{cm}^{-1}$$

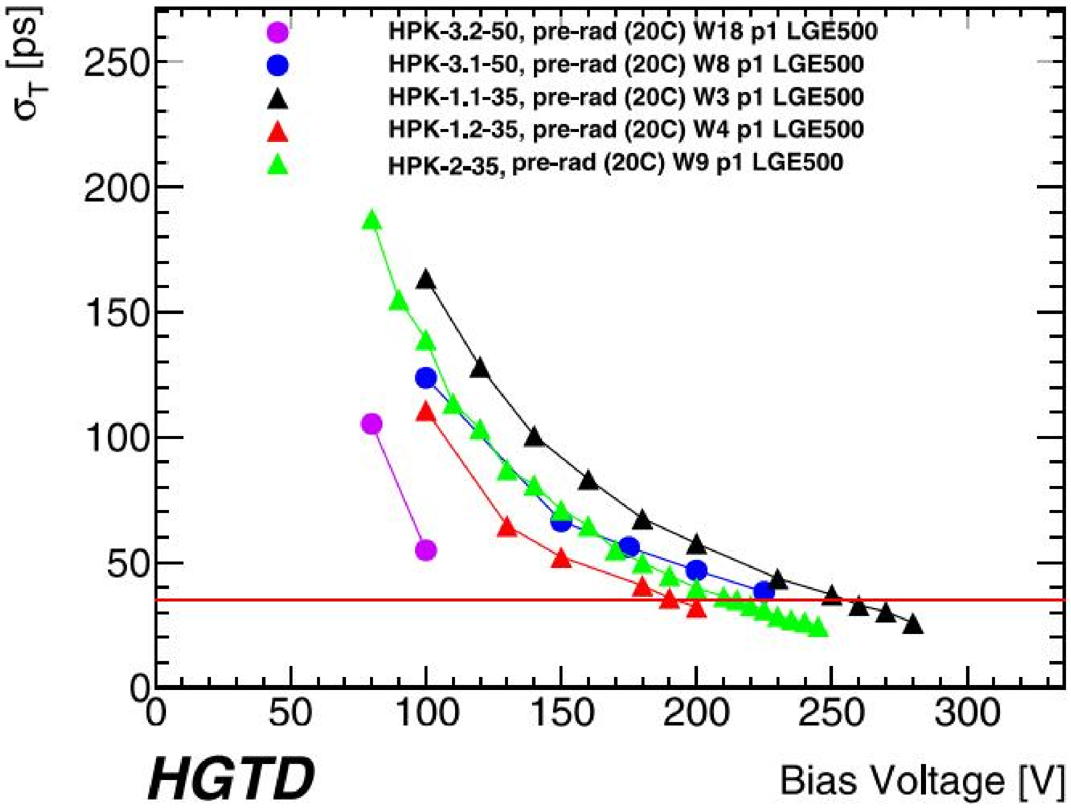
Excitation:

$$dN_{e-h\,pairs}(dVdt) = I'dVdt/h\nu$$



附录：时间分辨





RASER仿真得到LGAD探测器时间分辨为$30.4 \pm 0.4ps$，与实验结果[1]X.Yang etal,2020约35ps相符

附录：扩散信息(Diffusion Profile)

除定向漂移外的随机运动引入Langevin项

$$\Delta\vec{x}_{Langevin}\sim N(0,2Dt), D=\frac{k_BT\mu}{q}$$

非平衡载流子在电场中漂移和扩散的分布

高斯光束

$$N=\boxed{N_0\frac{1}{\sqrt{2\pi\tau^2}}exp(-\frac{t^2}{2\tau^2})\frac{1}{\sqrt{2\pi\sigma_0^2}}exp(-\frac{z^2}{2\sigma_0^2})}*\boxed{\frac{1}{\sqrt{2\pi\sigma_D^2}}exp(-\frac{(z-\mu Et)^2}{2\sigma_D^2})}$$

漂移与扩散

$$N(z,t)=\frac{1}{\sqrt{2\pi\tau^2}}exp(-\frac{t^2}{2\tau^2})*\frac{1}{\sqrt{2\pi\sigma^2}}exp(-\frac{(z-z_0-\mu Et)^2}{2\sigma^2}),\sigma^2=\sigma_0^2+2Dt$$

$$dz=\frac{d(\mu E)}{dz}dt,\frac{\partial\sigma^2}{\partial t}=D(z,t)$$

$$N(z,t+dt)=N_0exp(-\frac{[z\Big/(1+\frac{d(\mu E)}{dz}dt)]^2}{2(\sigma^2+Ddt)})$$

$$\frac{d\sigma^2}{dt}=\frac{k_BT}{q}\mu+2\sigma^2\frac{d(\mu E)}{dz}\rightarrow\rightarrow d\sigma^2=\frac{k_BT}{q}\frac{dz}{E}+2\sigma^2\frac{d(\mu E)}{dz}\frac{dz}{\mu E}$$

$$\sigma^2=\frac{(\mu_eE_e)^2}{(\mu_iE_i)^2}[\int_{z_i}^{z_e}\frac{k_BT}{q}\frac{dz}{E}\frac{(\mu_iE_i)^2}{(\mu E)^2}+\sigma_0^2]$$

附录：扩散信息(Diffusion Profile)

$$\sigma^2 = \frac{(\mu_e E_e)^2}{(\mu_i E_i)^2}[\int_{z_i}^{z_e} \frac{k_B T}{q}\frac{dz}{E}\frac{(\mu_i E_i)^2}{(\mu E)^2} + \sigma_0^2]$$

掺杂均匀分布 $E(z) = E(z_e) - qN_{eff}(z - z_e)/\varepsilon$

$$\sigma^2 = \frac{E_e^2}{E_i^2}[\sigma_0^2 + \frac{k_1}{2}(1 - \frac{E_i^2}{E_e^2})]，k_1 = \frac{k_B T}{q}\frac{\varepsilon}{qN_{eff}} = 2.8\mu m^2$$

到达增益层的载流子分布

$$N(z_e, t)dx = \frac{\alpha E_p}{h\nu}\frac{1}{\sqrt{2\pi[\tau^2 + (\sigma/v_e)^2]}}exp(-\frac{(t - z_0/v_e)^2}{2\tau^2 + 2(\sigma/v_e)^2})exp(-\alpha x)dx$$

$dN = Ndt$,增益后产生MdN个增益空穴，增益信号$I_q \propto MdNv_e' q/d$，则

$$(\frac{dI_q}{dt})_{max} = \frac{k_2 E_p}{\sigma_{eff}(z)}, \boxed{k_2 = \frac{M}{\sqrt{2\pi}}\frac{v_e v_e'}{d}\frac{q}{h\nu} = 1.20 \times 10^{15}\frac{A \cdot m}{s \cdot J}}$$

激光和探测器性质决定探测器

$$\frac{1}{\sigma_{eff}(z)} = \int_0^{x_{max}} \frac{exp(-\alpha x)\alpha dx}{\sqrt{\tau^2 v_e^2 + \frac{E_e^2}{E_i^2}[\frac{\omega_0^2(x)}{4} + \frac{k_z}{2}(1 - \frac{E_i^2}{E_e^2})]}}$$