A Theoretical Investigation of the Influence of High Irradiation on Signal to Noise Ratio (S/N) of Different Types of Active Pixel Sensors.

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FRONTIER DETECTORS FOR FRONTIER PHYSICS

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The motivation of this investigation is to find an optimal geometry of a single pixel element. It can be useful for developing of new Pixel Detector (PD) with high radiation hardness. A simplified mathematical model based on the differential equation for charge transport is used to describe a process of diffusion and drift in the pixel diode. The model is used to estimate the dependence of the S/N ratio for the Full Depleted FDAPS, the Monolithic Active Pixel Sensor (MAPS) and Hybrid Technology HPD on the radiation absorbed dose. We have also studied the dependence of the S/N ratio on the geometry of the pixel diode's area.

Detector technology and geometry

The Monolithic Active Pixel Sensor (MAPS)

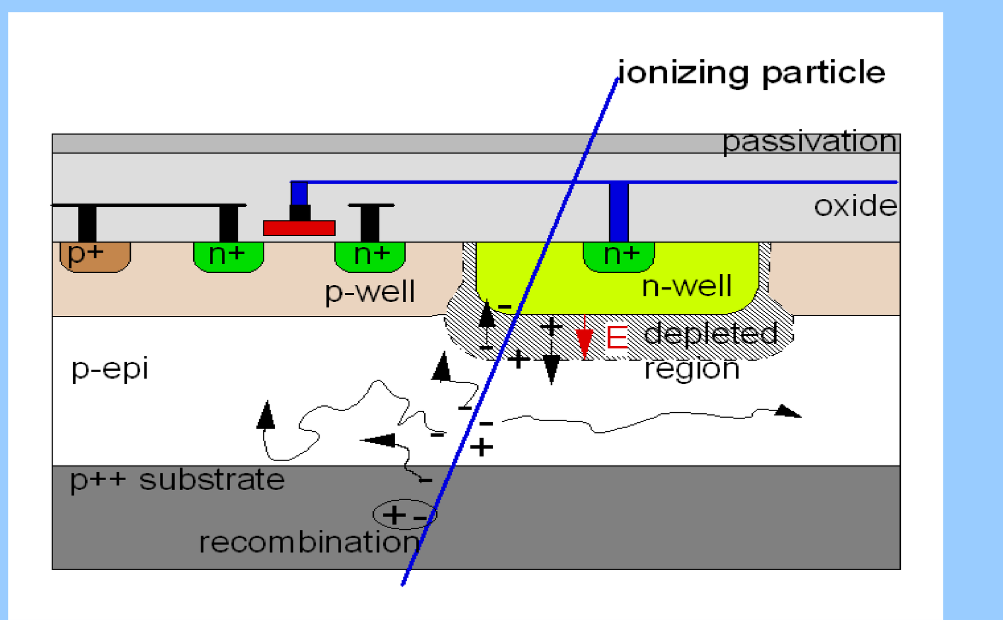

Figure 1: Principle of operation of the MAPS based on the PN diode. Output current is a current in a semiconductor caused by the diffusion of electrons.

We calculate a ratio of the active area S_{active} to total area S_{total} of the APS (see formula 0). The figure 2,b shows the dependence S_{active}/S_{total} on parameter k, where k=b/a (see Fig.2,a).

$$\frac{S_{active}}{S_{total}}=1+\frac{l}{a}\cdot\left\{\frac{(M-1)}{k\cdot M}+\frac{(N-1)}{N}\right\}+\left(\frac{l}{a}\right)^2\cdot\left\{\frac{(N-1)\cdot(M-1)}{k\cdot N\cdot M}\right\} \qquad (0)$$

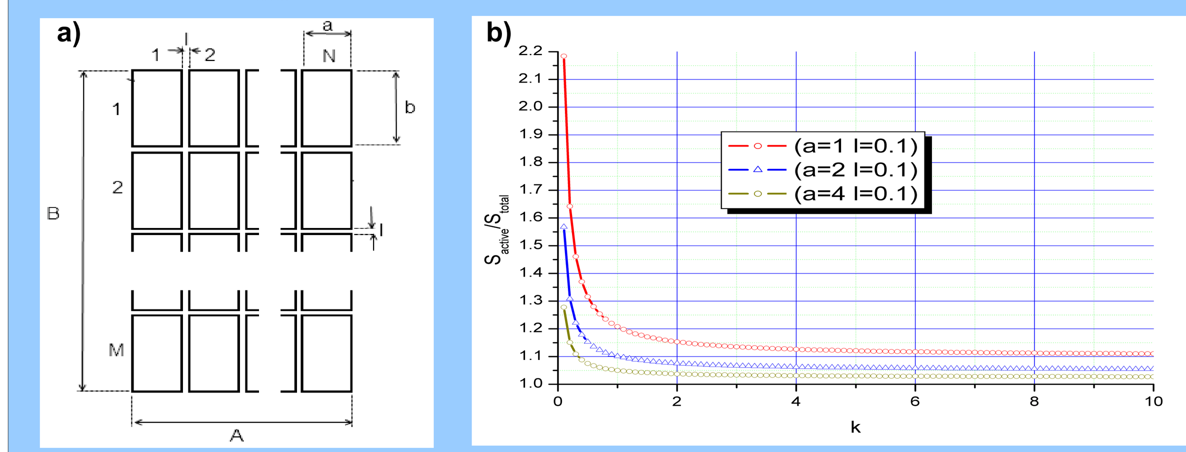

Figure 2: a) Geometry of the typical pixel detector consisted of a group of the elements (diodes), where *A,B* are sizes of the pixel detector; *a,b* are sizes of the active area; *l* is dead space between pixel elements,*N/M* are numbers of the elements in row/column;
b) The dependence of the ratio S_{active}/S_{total} on parameter *k*

Full/partially depleted active pixel sensor (FDAPS) and hybrid pixel detector (HPD) have the similar structure. Let's call them APS.

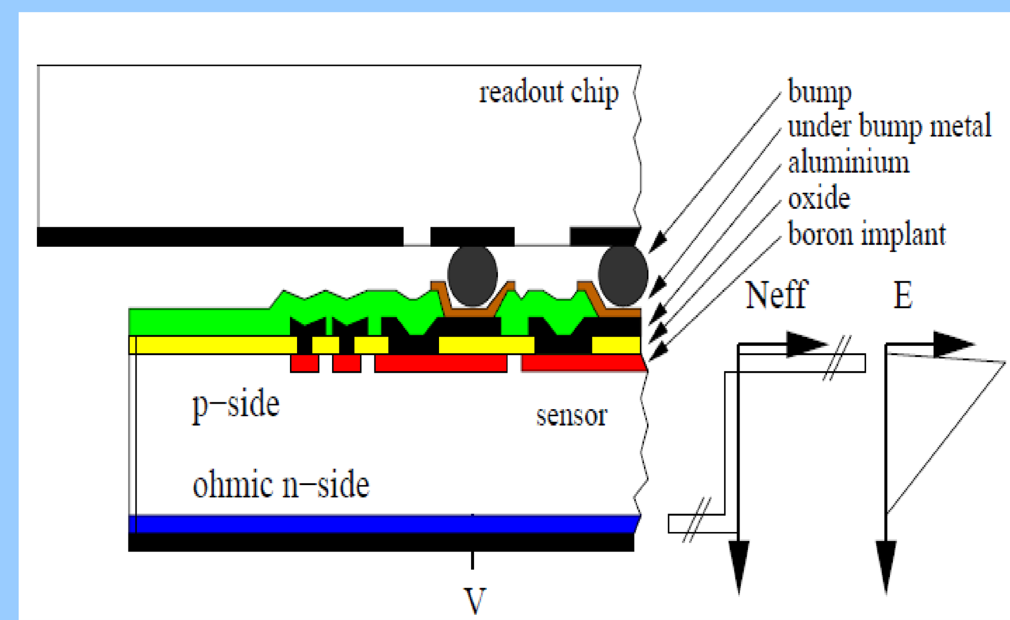

Figure 3: Structure of the FDAPS/HPD based on the PIN diode. Output current is a current in a semiconductor caused by the drift of electrons in the electric field.

Physical models

Model #1 (Transport electron by drift): Let's calculate the drift current (I_{drift}) generated by a MIP in a PIN diode . We use the equations [1]:

$$\frac{dn}{dt}=\frac{\partial n}{\partial t}+\mu_e\cdot E\cdot\frac{\partial n}{\partial x}$$

$$\frac{\partial E}{\partial x}=\frac{-e\cdot N_d}{\epsilon_o\cdot\epsilon_{Si}}$$

$$I(t)_e=\frac{e}{W_n}\cdot\mu_e\cdot\int(n(x,t)\cdot E(x)\,dt)$$

The solution is:

$$I(t)_e=\frac{e}{W_n}\cdot\mu_e\cdot\exp\left(\frac{e\cdot\mu_e\cdot N_d}{\epsilon_o\cdot\epsilon_{Si}}\right)\cdot\left[E_o\cdot(W_n-\xi(t))+\frac{e\cdot N_d}{\epsilon_o\cdot\epsilon_{Si}}\cdot(W_n^2-\xi(t)^2)\right] \qquad (1)$$

where: $\xi(t)=\frac{E_o\cdot\epsilon_o\cdot\epsilon_{Si}}{e\cdot N_d}\left(1-\exp\left(\frac{-e\cdot\mu_e\cdot N_d}{\epsilon_o\cdot\epsilon_{Si}}\right)\right)$

Model #2 (Transport electrons by diffusion): The diffusion current (I_{diff}) generated by a MIP in a PN diode can be obtained :

$$\frac{\partial n}{\partial t}\approx D_n\cdot\frac{\partial n}{\partial x}$$

We can propose the solution in the next form :

$$I_{diff}(t)\approx\frac{e\cdot N_e}{\frac{D_n}{L_n}\cdot\delta(t)} \quad \text{where} \quad \delta(t)\approx\left(1-K\cdot\frac{t}{T_{coll}}\right) \quad T_{coll}\text{ – collection time, and } K\leq 1 \qquad (2)$$

The noise of PIN diode is defined by leakage currents [2]:

$$I_{PIN}(V)=e\cdot S\cdot\left[\left[\frac{D_n\cdot N_i^2}{L_n\cdot N_d}+\frac{Wn(V)\cdot N_i}{\frac{2\cdot L_n^2}{D_n}}\right]+G\cdot Wn(V)\cdot N_i\right]\cdot\left(1+\exp\left(-\frac{V}{\phi_T}\right)\right) \qquad (1a)$$

The noise of PN diode is defined by leakage currents [2]:

$$I_{PN}(V)=e\cdot S\cdot\left[\frac{D_n\cdot N_i^2}{L_n\cdot N_d}+G\cdot Wn(V)\cdot N_i\right]\cdot\left(1+\exp\left(-\frac{V}{\phi_T}\right)\right)$$

The signal to noise for Johnson noise of resistor R_{eq} [3]:

$$\frac{S}{N}=\frac{I_{signal}^2\cdot R_{eq}}{\langle I_{leak}\rangle^2\cdot R_{eq}} \qquad (2a)$$

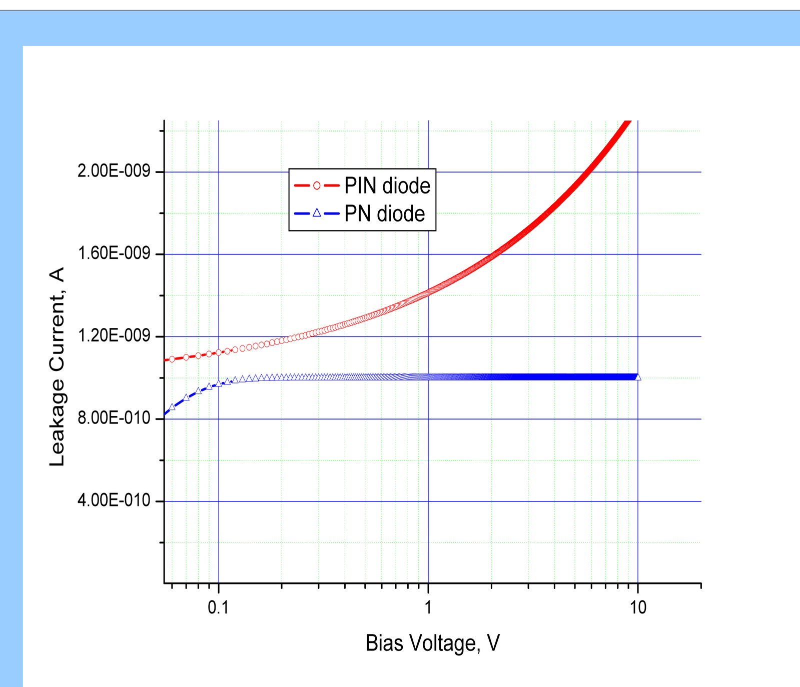

Figure 4: Dependence of the leakage current on voltage for the PIN diode (red line) and the PN diode (blue line). The values were calculated from the equations (1a) and (2a).

Signal and noise

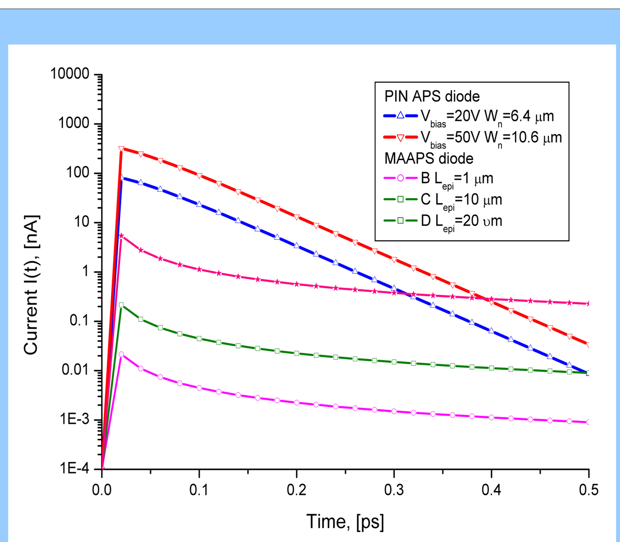

Figure 5: Signals as a dependence of the current on time for the PIN and the PN diodes. The values were calculated from the equations (1) and (2).

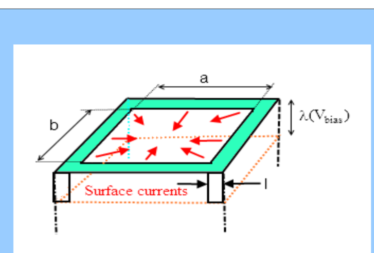

Figure 6: Scheme of the leakage current thermally generated in a diode near surface.

Ratio of the leakage currents generated in a bulk and near surface can be estimated:

$$\frac{I_{bulk}}{I_{surf}}\approx\frac{\tau_t}{\tau_i}\cdot\frac{N_i}{N_t}\cdot\frac{W(V_{bias})}{\lambda(V_{bias})\cdot l}\cdot F(k,a)$$

where:

$$F(k,a)=\frac{a\cdot b}{2\cdot(a+b)} \qquad (3)$$

Formula (3) gives us a trap concentration (Fig.7) for different *k* and *a*, when $I_{surf}=I_{bulk}$

- N_i -- intrinsic concentration electrons in Si
- N_t -- traps concentration in bulk near surface
- $W(V_{bias})$ –- depth of depletion region
- $\lambda(V_{bias})$ — depth of surface potential
- T_i — life time of electrons
- T_t — life time of electron traps
- V_{bias} — bias voltage

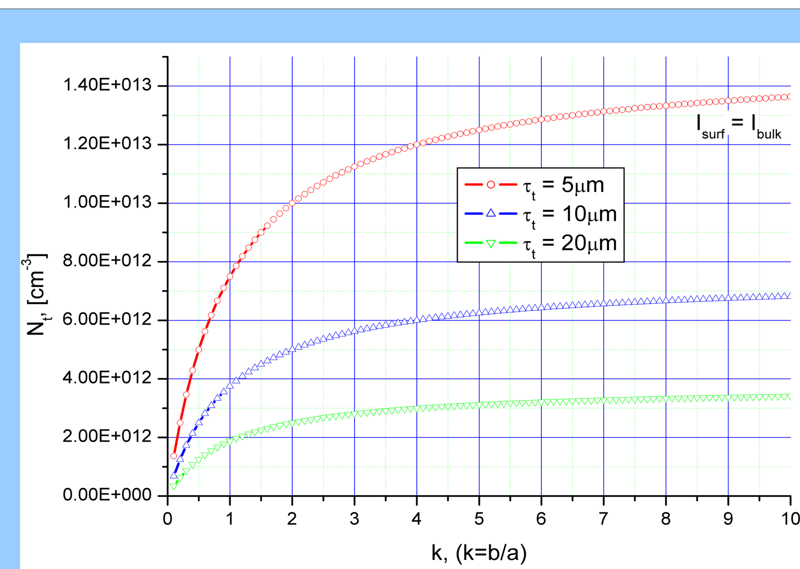

Figure 7: The dependence of the traps concentration on parameter *k=b/a* for different lifetime of traps. For long trapping lifetime the level of noise is high.

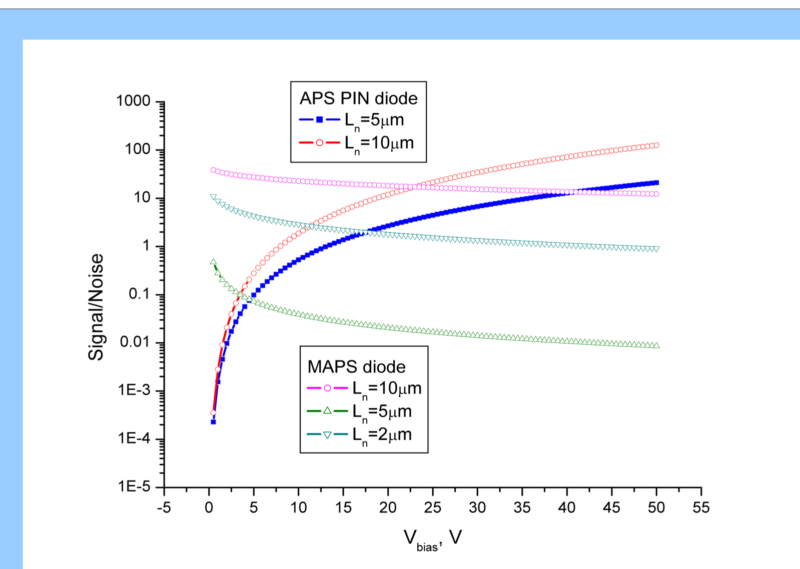

Figure 8: Dependence of the S/N ratio for the PIN and the PN diodes on bias voltage for different length of diffusion. The S/N of MAPS is better for low bias voltage. The voltage for the case $S/N_{(MAPS)}=S/N_{(APS)}$ can be found from this distribution.

Radiation influence

Both figures Fig.9 and Fig.10 are resuts of the calculations using the physical model #1 and model#2.

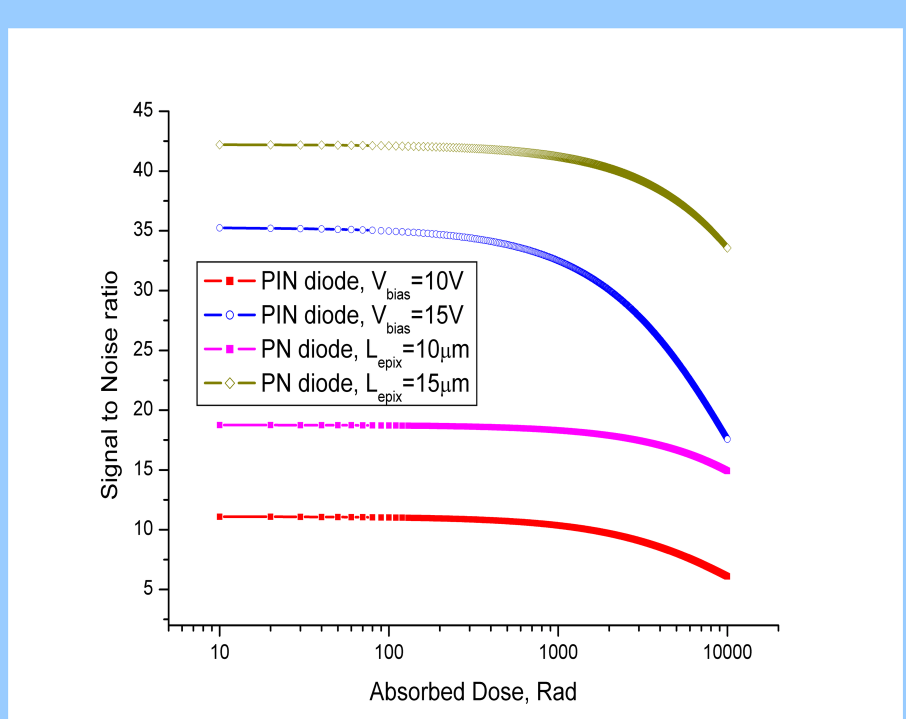

Figure 9: Dependence of the S/N ratio on an absorbed dose of 1-MeV electrons for the PIN(red,blue) and PN (green,pink). Dependence of lifetime on the dose was taken from: V.N. Bhoraskar et al., NIM B62, 1991, pp.99-102

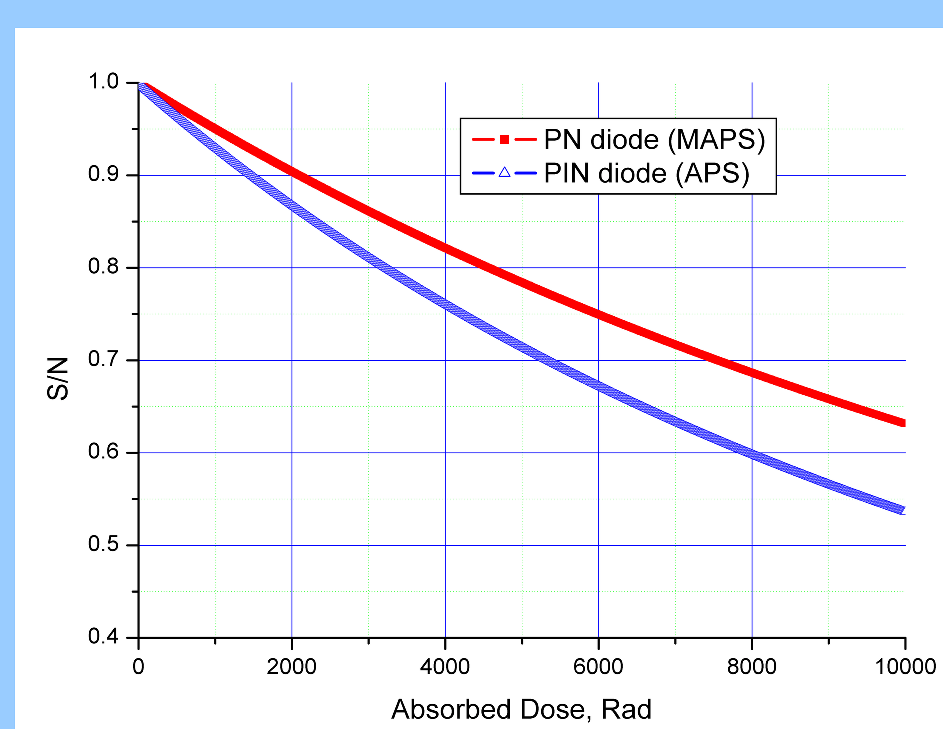

Figure 10: Dependence of the S/N ratio on an absorbed dose of 1-MeV electrons for the PIN(blue) and PN (red). The value of the S/N ratio was normalized to maximal value.

Conclusions

The theoretical investigation allowed us to conclude:

1. Active area of the APS could be more effectively used for asymmetric (b/a>2) geometry;
2. To minimize the leakage current thermally generated in a diode near surface it is possible to choose the ratio b/a in the case if the trapping lifetime is fixed;
3. We observe that the S/N ratio for the MAPS decreases with increasing bias voltage, while it is well known that for the APS it increases with increasing bias voltage;
4. Absolute value of the S/N ratio for the MAPS is larger than for the S/N ratio for APS (in the frame of considered model);
5. For the irradiated APS and MAPS detectors we have studied the S/N ratio dependence on absorbed dose. S/N ratio decreases with increasing dose. Moreover, for the APS detector this decrease is faster than for the MAPS.

Acknowledgements & References

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[1] Eremin, V. Chen, W. Li, Z "Analytical Solutions Of Minimum Ionization Particle Induced Current Shapes Of Silicon Detectors And Simulation Of Charge Collection Properties".Nuclear Science Symposium and Medical Imaging Conference, 31 Oct-6 Nov 1993, pp. 292 — 296

[2] Rolf Enderlein, " FUNDAMENTALS OF SEMICONDUCTOR PHYSICS AND DEVICES", 1997

[3] John C. Russ (2007). The image processing handbook. CRC Press. ISBN 0-8493-7254-2.