8th Pisa Meeting on Advanced Detectors, Isola d'Elba, May 21-27, 2000

A Simple Model of Charge Collection in Silicon Detectors

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ABSTRACT

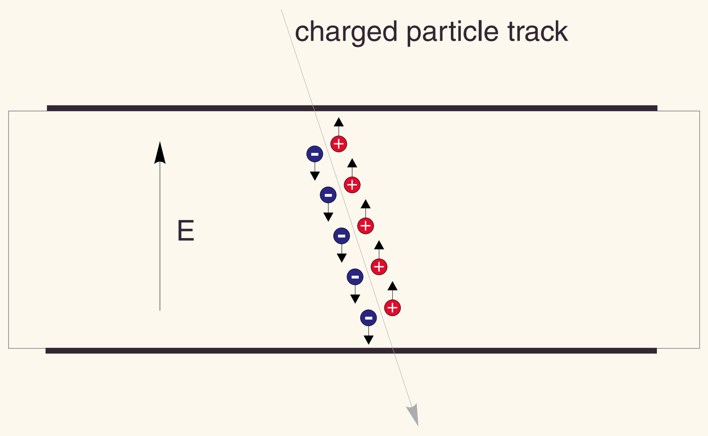
The charge collection and the resulting currents of electrons and holes in silicon detectors are described well by a simple model derived from the basics of semiconductor theory. Depending on various parameters like resistivity, bias voltage and thickness, we calculate the currents resulting from charge movement across the detector. In heavily irradiated silicon detectors, the bulk converts from n- to p-type and the pn-junction moves from the readout side to the backplane side. Nevertheless, neglecting trapping due to radiation damage, it can be shown that the overall currents before and after this inversion are the same although the single carrier contributions are quite different. Furthermore the detector currents are applied to a model of the APV amplifier with CR-RC shaping and deconvolution. The amplifier output is shown for several parameter settings.

MOTIVATION

- CMS Tracker
  - $230m^2$ silicon detectors
  - 300µm and 500µm thick
- Studying charge collection in thick detectors under LHC conditions

MODEL

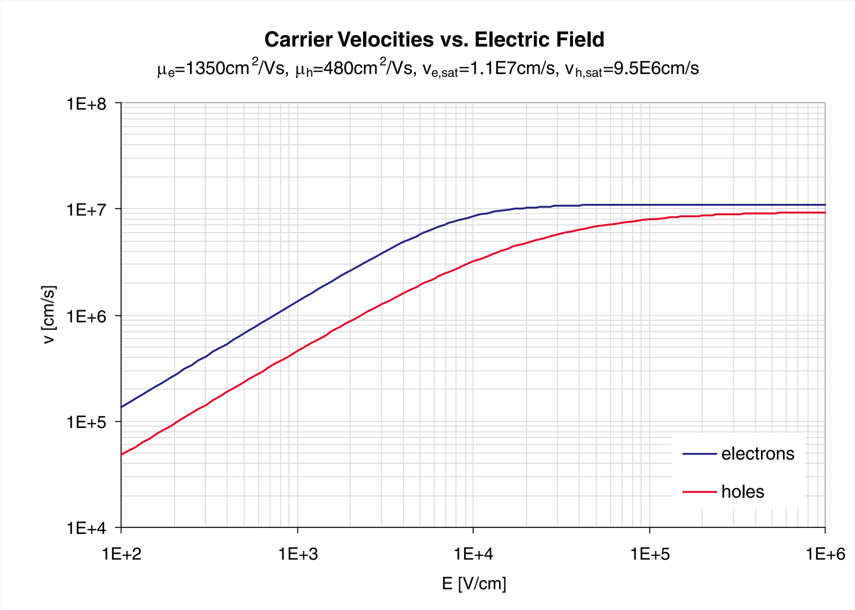
- Charged particle traverses detector
  - e/h pair generation along track



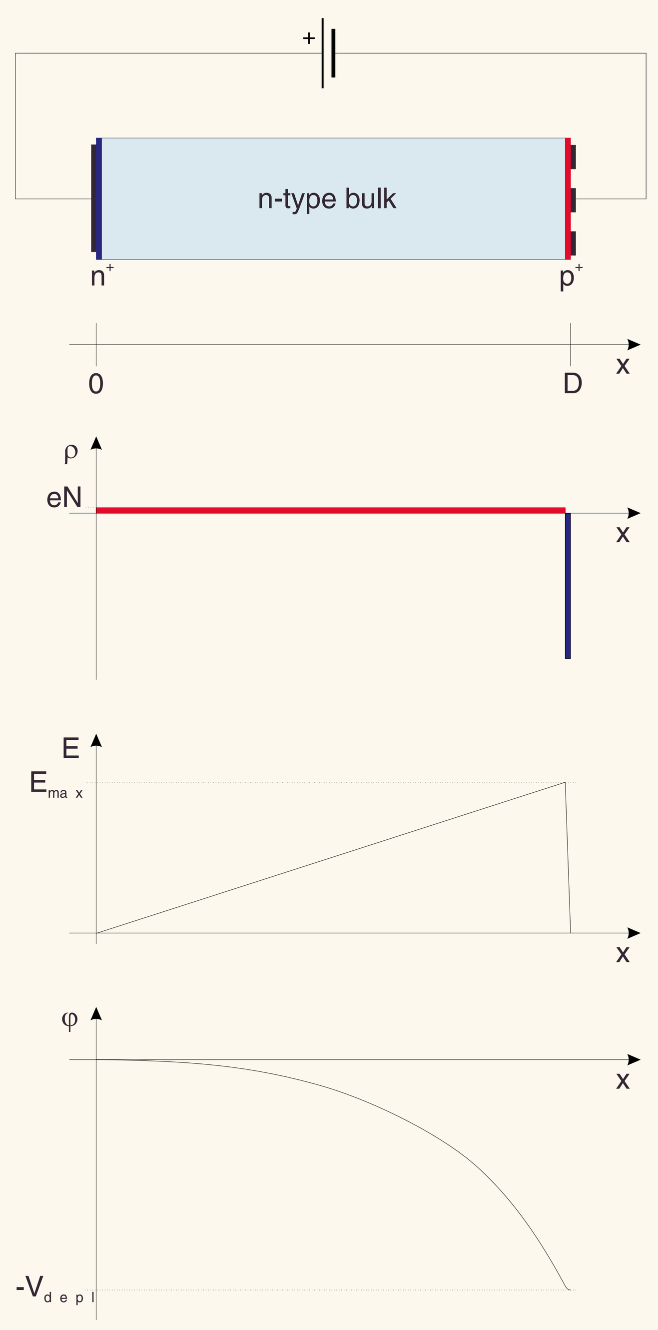
- Charges move under the influence of an electric field

$$v_e = \frac{\mu_e E}{\sqrt{1+\left(\frac{\mu_e E}{v_{e,\mathrm{sat}}}\right)^2}}$$

$$v_h = \frac{\mu_h E}{1+\frac{\mu_h E}{v_{h,\mathrm{sat}}}}$$



- Electric field



$$N = \frac{1}{r e \mu_e}$$

$$\frac{dE}{dx} = \frac{\rho}{\epsilon}$$

$$E_{\max} = \frac{END}{\epsilon}$$

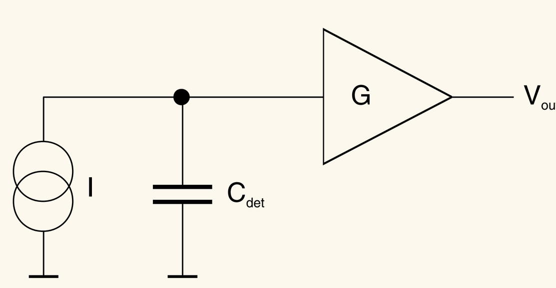
$$\frac{d\varphi}{dx} = -E$$

$$V_{\mathrm{depl}} = \frac{D^2}{2 r \mu_e \epsilon}$$

  - Full depletion: triangular field shape
  - Overdepletion: offset adds
  - Below full depletion: Zero field region → charge collection is inefficient
- Carrier movement induces current in the circuit

$$i = \frac{e}{D}\left(\sum v_e + \sum v_h\right)$$

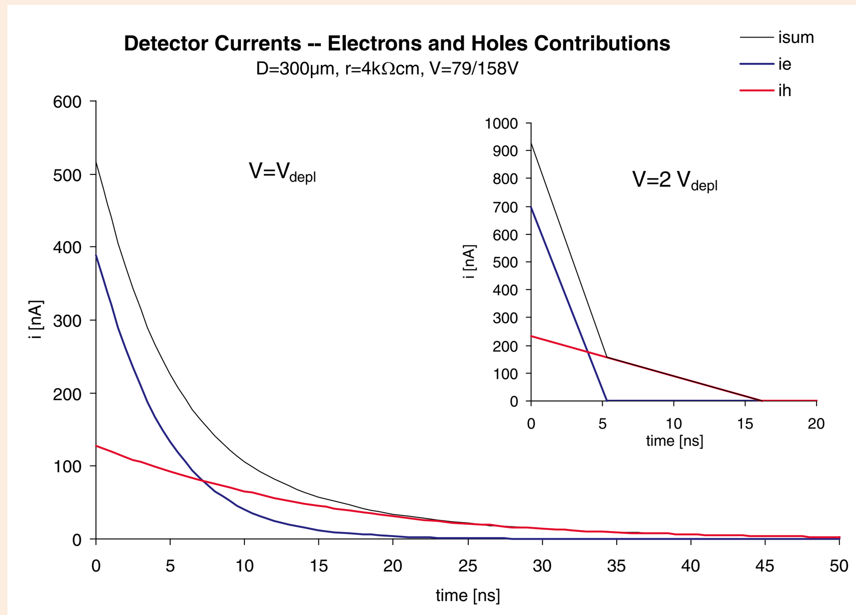
- Calculating carrier movements in finite steps
  - Concentrated "supercharge" clusters to save calculation time
- Fast CR-RC shaping amplifier (APV series)



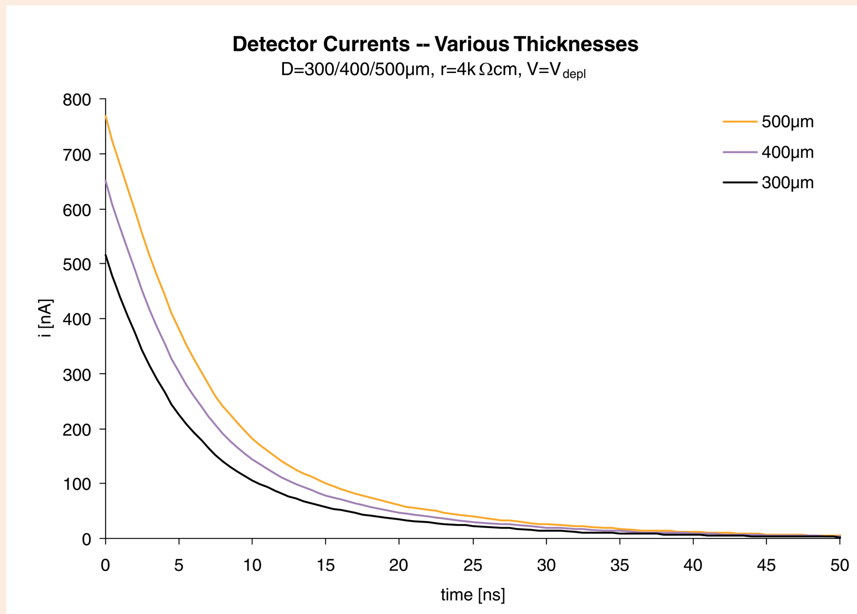
$$V_{\mathrm{out}} = I \frac{T_p}{C_{\mathrm{det}}(1+sT_p)^2}$$

RESULTS

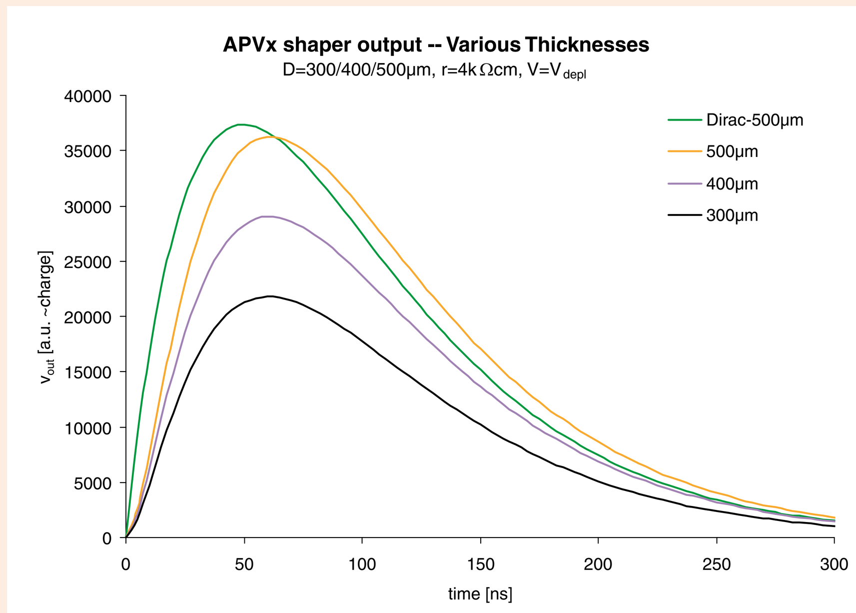
- Standard 300µm silicon detector
  - Approximately exponential currents at $V=V_{depl}$
  - Currents become linear at higher bias



- Sensor thickness variation ($V=V_{depl}\sim D^2$)
  - Currents scale almost perfectly with thickness
  - Longer carrier drift path is compensated by higher electric field
  - Only carrier velocity saturation makes small difference

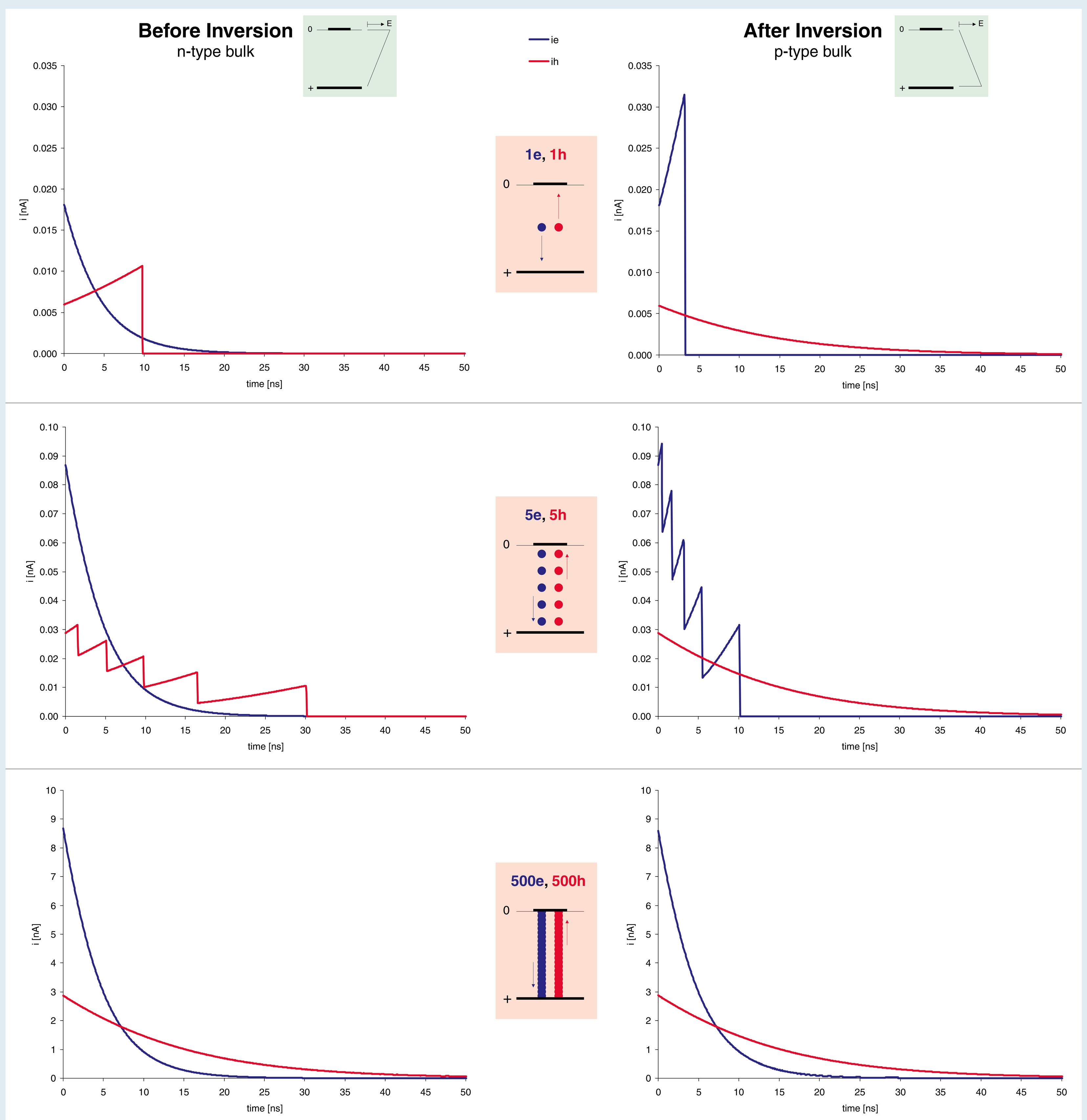


- Fast CR-RC shaper output (APVx, T_p=50ns)
  - Output scales perfectly with thickness
  - Integrating behavior of shaper
  - Same robustness with deconvolution algorithm



INVERSION

- Heavy irradiation converts n-type bulk to p-type
  - pn-junction moves from readout to backplane side
  - Electric field shape flips



  - Overall currents are the same although individual contributions vary

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