Chapter 1

Signal formation in diamond

A sensor converts the energy deposited by a particle or a photon and to an electrical signal. There are many types of sensors existing, but in this chapter we will focus on semiconductors, in particular on diamond sensors. Diamond is a good insulator, but behaves as a semiconductor in certain cases. Section 1.1 explains in detail the energy deposition and signal formation mechanism whereas the section 1.3 focuses on signal amplification and acquisition. Noise contributions are discussed at every stage of the signal chain.

Table 1.1 compares the properties of diamond and silicon.

Table 1.1: Comparison diamond – silicon

Property	Diamond	Silicon
Band gap energy E_g (eV)	5.5	1.12
Electron mobility μ_e (cm^2 V^{-1} s^{-1})	1800	1350
Hole mobility μ_h (cm^2 V^{-1} s^{-1})	1200	450
Breakdown field (V cm^{-1})	10^7	3×10^5
Resistivity (Ω cm)	$> 10^{11}$	2.3×10^5
Intrinsic carrier density (cm^{-1})	$< 10^3$	1.5×10^{10}
Mass density (g cm^{-1})	3.52	2.33
Atomic charge	6	14
Dielectric constant ε	5.7	11.9
Displacement energy (eV/atom)	43	$13 - 20$
Energy to create an e-h pair (eV)	13	3.6
Radiation length (cm)	12.2	9.6
Avg. signal created/μm (e)	36	89

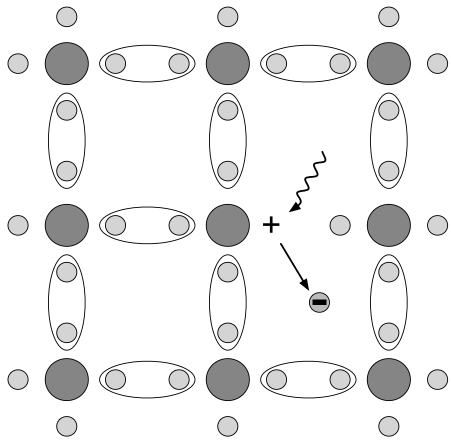


Figure 1.1: Valence bonds in the crystalline structure can be broken, producing a free electron-hole pair

1.1 Principles of signal formation in semiconductors

Lattice, electron-hole pair production (3 pg) Ramo theorem (2 pg) SC detector systems, pg. 43-73

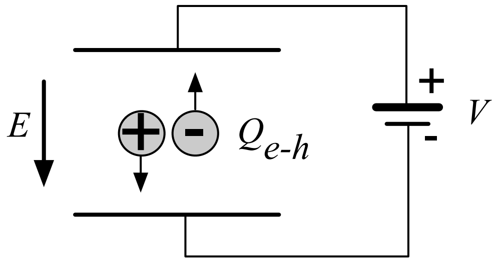
Semiconductors are materials that are that are conductive only under specific conditions. They can be made up of atoms with four electrons in their valence band (e.g. silicon–Si, carbon–C or germanium–Ge) or as combinations of two or more different materials (e.g. gallium arsenide–GaAs).

The atoms form valence bonds with adjacent atoms, making solid crystal structures. These bonds break if sufficient external energy is applied. The electron that was forming the bond is kicked out, leaving behind a positively charged ion with a vacancy in its valence band (see figure 1.1). A free electron-hole pair is thus created. The free electron travels through the crystal until it is caught by another hole. Similarly, the hole also "travels" through the material. Its positive charge attracts a bound electron in the vicinity, which breaks from the current bond and moves to the vacancy, leaving a new hole behind. The process continues, making it look like the vacancy – hole is traveling through the material.

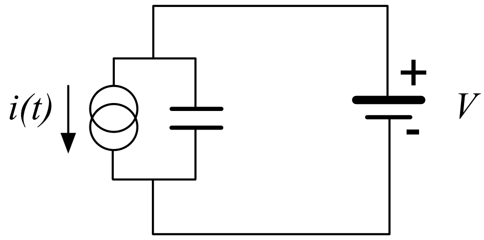
If an external electric field is applied to the crystalline structure, the free electrons and holes drift toward the positive and negative potential, respectively (see figure 1.2a). While drifting, the charges couple with the electrodes, inducing current in the circuit. They recombine upon reaching the electrodes.

The electrons need to absorb a certain energy to get kicked out of the atomic bond – ionised. The minimal energy required to excite (ionise) an electron in a semiconductor is equal to the energy gap E_g. Typical widths of the forbidden gap are 0.7 eV in Ge, 1.12 eV in Si, 1.4 eV in GaAs and 5.5 eV in Di.

Due to the small band gap in semiconductors some electrons occupy the con-



(a) An electron-hole pair drifting in electric field



(b) Equivalent circuit

Figure 1.2: Electron-hole drift representation in a circuit

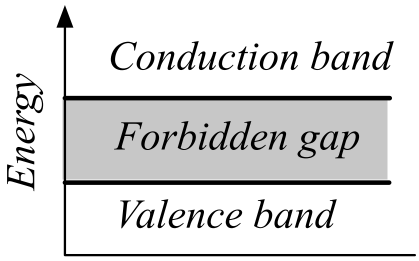


Figure 1.3: Energy states of an electron

duction band at room temperature (RT). The intrinsic carrier concentration n_i in semiconductors is given as

$$n_i = T^{3/2} \cdot exp(-\frac{E_g}{2kT}) \tag{1.1}$$

wherein $k = 1.381 \cdot 10{-}23m^2kgs{-}2K{-}1$ is the Boltzmann constant and T is the temperature.

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Thermal noise in semiconductors

1.1.1 Signal charge fluctuations

Two of the important sensor characteristics are the magnitude of the signal and the fluctuations of the signal at a given absorbed energy. They determine the relative resolution ΔE/E. For semiconductors the signal fluctuations are smaller than the simple statistical variance $\sigma_Q = \sqrt{N_Q}$, where N_Q is the number of released charge pairs (ratio between the total deposited energy E_0 and the average emergy deposition E_i required to produce a charge pair). In fact, [] shows that the variance is $\sigma_Q = \sqrt{FN_Q}$, where F is the Fano factor [] (0.08 for diamond and 0.115 for silicon []).

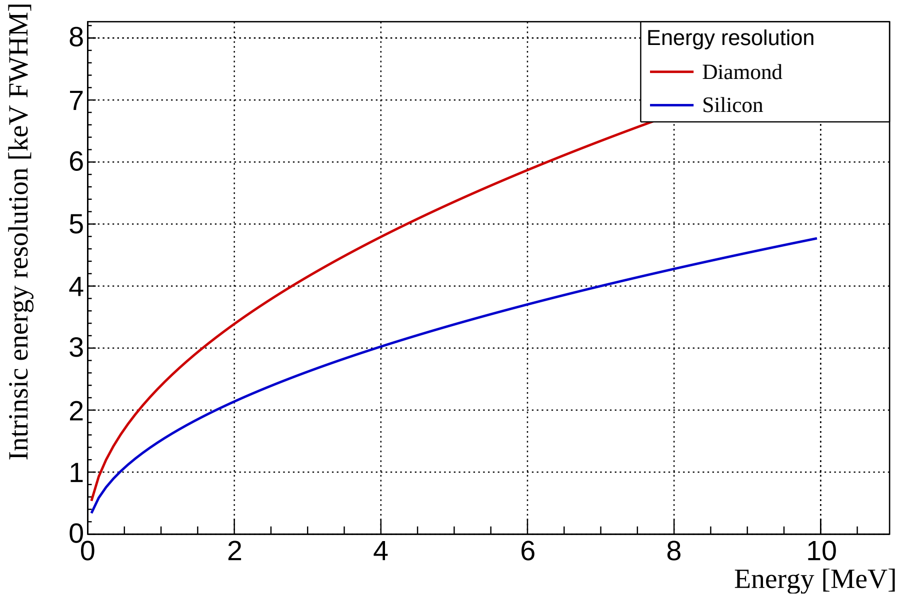

Figure 1.4: Intrinsic energy resolution for silicon and diamond

Thus, the variance of the signal charge is smaller than expected, $\sigma_Q \approx 0.3\sqrt{N_Q}$. The resulting intrinsic resolution of semiconductor detectors is

$$\Delta E_{FWHM} = 2.35\sqrt{FEE_i} \tag{1.2}$$

wherein Si E_i= 3.6 eV and C E_i= 13 eV. E.g., for an αparticle with energy $E_\alpha = 5.486$ MeV the calculated $\Delta E_{\alpha FWHM} = 5.6$ keV. Figure 1.4 shows the energy resolution function for silicon and diamond.

1.1.2 Signal formation

1.1.3 Radiation-induced electrical pulses

Theory: Examples - average pulses - persistence - gamma, beta, alpha
Current profiles Alpha beta gamma neutron

1.2 Carrier transport in a diamond sensor

This section describes the carrier transport phenomena in diamond. This theory provides the basis for discussion about the measurements in chapter **??**.

Free charge carriers in a semiconductor get thermally excited and scatter in random directions with a thermal velocity v_{th}. Their integral movement due to thermal excitation equals zero. Their transport is instead by means of drift and diffusion. Diffusion is caused by the concentration gradient. In its presence the carriers tend to scatter in the direction of the lower concentration. Drift on the other hand is caused by an externally applied electrical field. In that case the carriers move in parallel to to the field lines. In a sensor with a high applied field the diffusion contribution is negligible.

Diffusion The concentration profile dissolves with time forming a Gaussian distribution with variance $\sigma(t) = \sqrt{Dt}$.

Drift velocity and mobility The charge carriers drift through the diamond bulk with a drift velocity $v_{drift}(E)$, which is proportional to the electric field E at low electric fields: $v_{drift} = \mu E$. The proportionality factor μ is defined as the mobility in $\mathrm{cm^2V^{-1}s^{-1}}$. For higher fields, however, the velocity saturates. The final equation for v_{drift} is therefore

$$v_{drift}(E) = \mu(E)E = \frac{\mu_0 E}{1 + \frac{\mu_o E}{v_{sat}}} \tag{1.3}$$

where μ_0 is the low drift mobility and v_{sat} is saturation velocity. The drift velocity can be retrieved experimentally via the transit time measured with so-called Transient Current Technique (TCT). This technique enables the measurement of transit time t_t of the carriers through the sensor with the thickness d.

$$v_{drift}(E) = \frac{d}{t_t(E)}. \tag{1.4}$$

The velocities for holes and electrons usually differ.

Velocity saturation At higher velocities the carriers lose more energy to the lattice (phonon transport).

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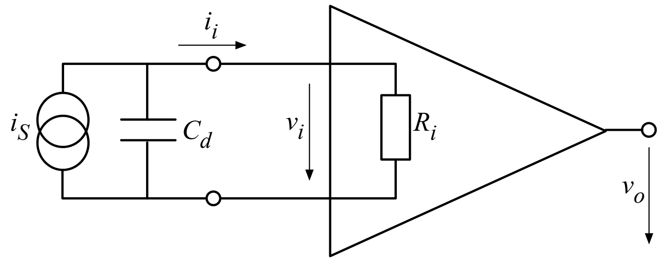

Figure 1.5: Simplified equivalent circuit of a capacitive source and a current amplifier

1.3 Electronics for signal processing

This section describes the electronics of a detector, starting with description of signal amplifiers and then discussing the digitisation and signal processing.

1.3.1 Signal preamplifiers

(2 pg) The signal charge generated in the sensor is of the order of fC and has to be pre-amplified before processing. The preamplifiers have to be designed carefully to minimise electronic noise while maximising gain – thus maximising signal-to-noise ratio (SNR). A critical parameter is the total capacitance, i.e. sensor capacitance and input capacitance of the preamplifier. Decreased capacitance improves the SNR.

Several types of amplifiers can be used, all of which affect the measured pulse shape. They behave differently for resistive or capacitive sources. Given that semiconductors are capacitive sources, we will focus on these. Two preamplifiers are used most commonly, a current and a charge amplifier. Both are described below in detail.

Current-sensitive amplifier

(0.5 pg) Figure 1.5 shows the equivalent circuit of a capacitive source and a current amplifier. An amplifier operates in current mode if the source has a low charge collection time t_c with respect to the RC time constant of the circuit. In this case the sensor capacitance discharges rapidly and the output voltage is proportional to the instantaneous current $v_o \propto i_s(t)$. The amplifier is providing voltage gain, so the output signal voltage v_o is directly proportional to the input voltage v_i.

Charge-sensitive amplifier

(0.5 pg) In order to measure integrated charge in the sensor, a feedback loop is added to the amplifier (see figure 1.6). The feedback can be used to control the gain and input resistance, as well as integrating the input signal. The charge amplifier is in principle an inverting voltage amplifier with a high input resistance.

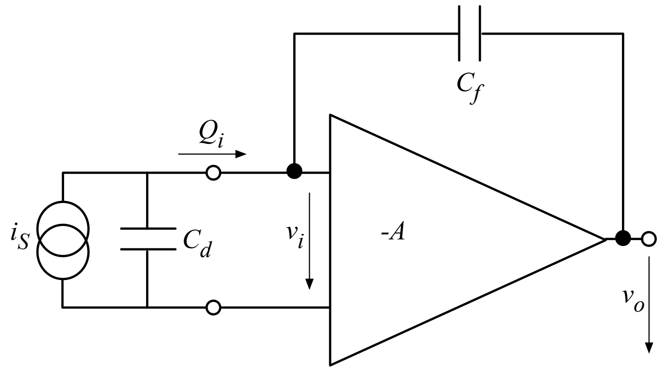

Figure 1.6: Simplified equivalent circuit of a capacitive source and a charge amplifier

In an ideal amplifier the output voltage v_o equals $-Av_i$. Therefore voltage difference across the capacitor C_f is $V_f = (A+1)v_i$ and the charge deposited on the capacitor $Q_f = C_f v_f = C_f(A+1)v_i$. Since no current can flow into the amplifier, all of the signal current must charge up the feedback capacitance, so $Q_f = Q_i$.

In reality, however, charge-sensitive amplifiers respond much slower to the than the time duration of the current pulse from the sensor.

Analogue electronic noise

(2 pg) Electronic noise determines the ability of a system to distinguish signal levels.

1.3.2 Analogue-to-digital converters

(1 pg) An analog-to-digital converter (ADC) is a device that converts analogue electrical signal on the input to its digital representation - a digital number. This involves a quantisation – *sampling* of the signal at a defined sampling period, resulting in a sequence of samples at a discrete time and a discrete amplitude. The resolution of the ADC is the number of output levels it can quantise to and is expressed in bits. For instance, an 8-bit ADC with an input voltage range of 100 mV and a sampling period of 1 ns would produce 1 GSPS (gigasample per second) at a voltage resolution Q of

$$Q = \frac{Input\ voltage\ range}{2^{\ resolution}} = \frac{100\ mV}{2^8\ ADCcounts} = 0.39\ mV/ADCcount \tag{1.5}$$

Quantisation error and quantisation noise

(1 pg) The quantisation error (or a round-off error) is a contribution of the digitisation to the overall measurement error. It is defined as a difference between the actual analog value and a digitised representation of this value.

Typically, the input signal amplitude is much larger than than the voltage resolution. Therefore the quantisation error is not directly correlated with the signal and has an approximately uniform distribution.

1.3.3 Signal processing

(1 pg) After signal amplification and digitisation the data can be either processed immediately or they can be saved to a data storage for later analysis. Below are the examples of systems that carry out the data processing on the fly.

Field programmable gate array

(0.5 pg) Field programmable gate array (FPGA) is an integrated circuit designed to be reprogrammable and configured after manufacturing. It consists of a set of logic gates that can be interconnected in numerous combinations to carry out a logic operation. Many such logic operations can take place in parallel, making the FPGA a powerful tool for signal processing.

Application-specific integrated circuit

FE-I4 functional description, characteristics (2 pg)

Application-specific integrated circuit (ASIC) is an integrated circuit designed for a specific use. The design cannot be modified after chip production, as opposed to FPGAs. On the other hand, the ASICs can be optimised to perform a required operation at high speed and low power.

1.3.4 Full detector readout chain

(1 pg)