Chapter 1

Signal formation in diamond

This chapter describes the fundamentals of signal formation in a diamond sensor, as well as its use as a particle detector. This is described in section 1.1 where energy deposition and signal formation mechanism are explained. Then some examples of ionisation are shown. Later, some of the internal lattice defects that effect the signal are described. The final section contains the description of the remaining part of the signal chain – signal amplifiers, digitisers and devices for signal processing. Noise contributions are discussed at every stage of the signal chain.

There are many types of radiation 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. In fact, the main principle of operation is the same for diamond, silicon and other semiconducting materials – ionisation. An impinging highly energetic charged particle ionises the atoms in the lattice, freeing electrons and holes, which then drift towards positively and negatively charged electrodes, inducing an electrical signal. A sensor converts the energy deposited by a particle or a photon and to an electrical signal.

Currenty, silicon is considered the industry standard for particle detection. However, there are some disadvantages of using silicon instead of diamond, due to significant differences in the material properties. In particular, the properties of silicon change significantly with radiation. For instance, the leakage current increases, which in turn increases shot noise and can lead to thermal runaway. In addition, due to induced lattice defects, which act as charge traps, its charge collection efficiency starts dropping quickly. Both are true for diamond as well, but on a much smaller scale.

Table 1.1 compares the properties of diamond and silicon. Some of these values will be revisited and used in the course of this thesis.

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

Table 1.1: Comparison diamond – silicon

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 in the lattice form valence bonds with adjacent atoms, making solid crystal structures. These bonds can break up 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.

The electrons need to absorb a certain energy to get kicked out of the atomic bond – to get 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 already occupy the conduction 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 $k = 1.381 \times 10^{-23}$ m^2 kg s^{-2} K^{-1} is the Boltzmann constant and T is the temperature.

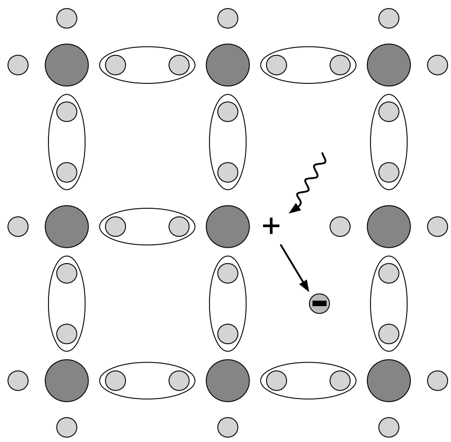
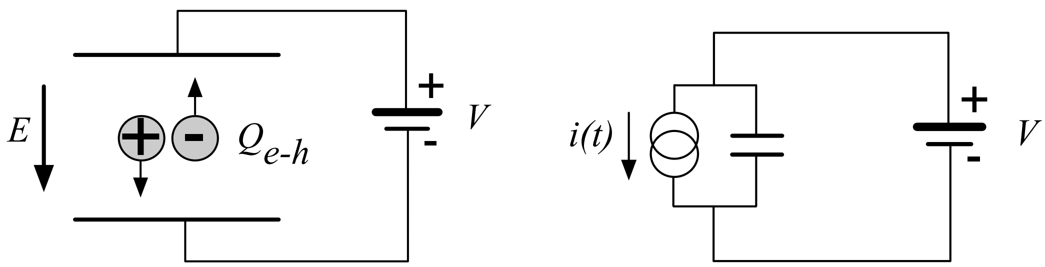


Figure 1.1: Valence bonds in the crystalline structure can be broken, producing a free electron-hole pair



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

(b) Equivalent circuit

Figure 1.2: Electron-hole drift representation in a circuit

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, which is explained by the Shockley–Ramo theorem []. The charges recombine upon reaching the electrodes.

There are several ways the particles can interact with the sensor: via bremsstrahlung [], elastic or inelastic scattering (e-h pair production). Bremsstrahlung is radiation created when a particle is deflected from its original path due to attraction of the core of an atom. This is in principle an unwanted effect in semiconductors as it decreases the spatial resolution of the sensor. Elastic scattering is deflection of the particle's trajectory without energy loss. Inelastic scattering is the interaction through which the atom is ionised and an electron-hole pair is created. All these effects are competing and are dependent on the particle's mass, momentum etc. The mean energy loss of a particle traversing the detector with respect to its momentum is given with the

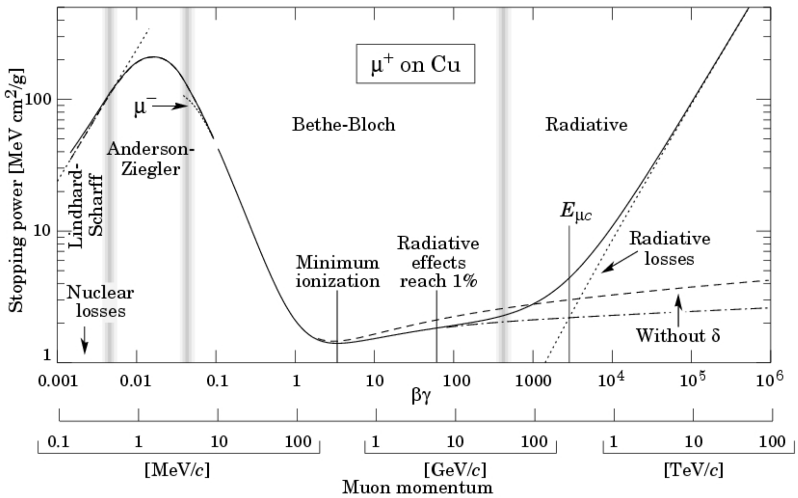


Figure 1.3: Stopping power for muons according to the Bethe-Bloch formula

so-called Bethe-Bloch equation 1.2:

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\epsilon_0} \right)^2 \cdot \left[ln \left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right] \tag{1.2}$$

The resulting function for a muon (a heavy electron) is shown in figure ??. At the momentum of around 300 MeV/c the particle deposits the lowest amount of energy. That is called a minimum ionising particle or a MIP.

1.1.1 Radiation-induced electrical pulses

When a highly-energetic particle travels through the sensor, it interacts with atoms in the lattice. It ionises the valence electrons, creating electron-hole (e-h) pairs on its way. It can either deposit only a fraction of its energy and fly exit the sensor on the other side or it can get stopped in the bulk, depositing all of its energy. A special case is when it interacts with the core of the atom in the middle of the sensor via a nuclear interaction. All these various types interactions produce different amounts and different spatial distributions of e-h pairs. The induced electrical current will therefore differ for different types of interaction. Two most frequent types are shown in the diagrams below. The first diagram shows the interaction of a minimum ionising particle (an electron or a proton) or in some cases a photon, if it is energetic enough. The electrons and holes are created all along the trajectory of the particle and immediately start drifting towards the positive and negative electrode, respectively. At the beginning, all charges drift and contribute to the induced current. Those closest to the electrodes have a very short drift path and recombine quickly, reducing the induced current. Gradually all the charge carriers recombine. The resulting current signal is a triangular pulse with a sharp rising edge and a linear falling edge. The accumulated charge Q_s equals to the sum of the contributions of the positive and negative charge carriers. The second type of interaction happens when the particle is stopped in the diamond close to the point of entry. Most of its energy is deposited in one point. A cloud of charge carriers is created and the charges with the shorter path to the electrode recombine almost instantly. The carriers of the opposite charge, however, start drifting through the sensor to the other electrode. In an ideal diamond sensor, their velocity is constant throughout the drift up until they recombine on the other side. The contribution of the first charge cloud is a peak with a short time. The cloud drifting through the sensor, on the other side, induces a current signal with a flat top. The resulting signal is rectangular shaped, with a spike in the beginning. This spike is filtered out in a real device because it is too fast for the electronics existing currently. The accumulated charge Q_s is equal to a half of the deposited charge by the stopped particle.

As seen the two types of interactions have well defined signal responses. Nuclear interactions on the other hand yield various results. The resulting signal shape depends on the decay products of the interaction – they can be α, β or γ quanta, inducing a mixed shaped signal.

1.1.2 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 []). 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

$$\Delta E_{FWHM} = 2.35\sqrt{FEE_i} \tag{1.3}$$

wherein $E_i(Si)$= 3.6 eV and $E_i(C)$= 13 eV. E.g., for an α particle with energy E_α = 5.486 MeV the calculated $\Delta E_{\alpha FWHM}$ = 5.6 keV. This defines the minimum achievable resolution for energy spectroscopy with diamond. Figure 1.4 shows the calculated energy resolution function for silicon and diamond.

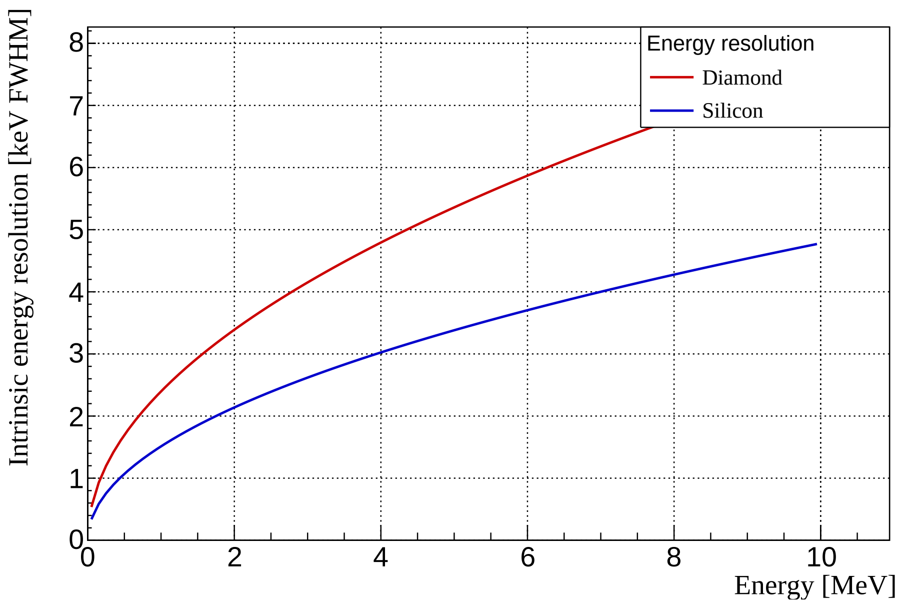


Figure 1.4: Calculated intrinsic energy resolution for silicon and diamond

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

$$v_{drift}(E) = \mu(E)E = \frac{\mu_0 E}{1 + \frac{\mu_o E}{v_{sat}}} \tag{1.4}$$

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.

$$v_{drift}(E) = \frac{d}{t_t(E)}. \tag{1.5}$$

The velocities for holes and electrons usually differ.

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

Space carge

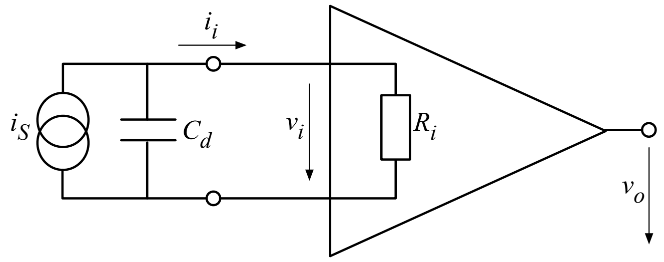


Figure 1.5: Simplified equivalent circuit of a capacitive source and a current amplifier

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.

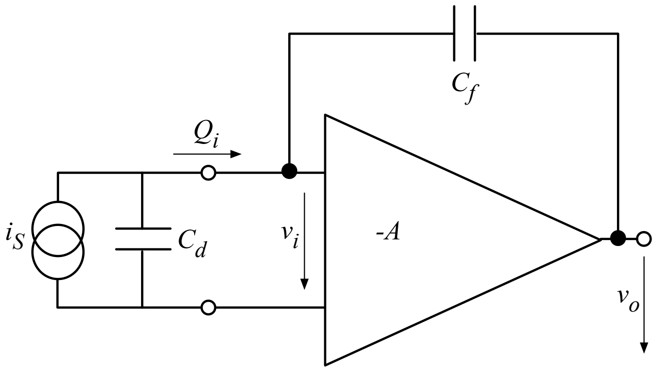


Figure 1.6: Simplified equivalent circuit of a capacitive source and a charge amplifier

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

$$Q = \frac{Input\ voltage\ range}{2\ ^{resolution}} = \frac{100\ mV}{2^8\ ADCcounts} = 0.39\ mV/ADCcount \tag{1.6}$$

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)