12
Ageing and radiation effects

Life would be infinitely happier if we could only be born at the age of eighty and gradually approach eighteen.

Mark Twain

12.1 Ageing effects in gaseous detectors

Ageing processes in gaseous detectors are about as complicated and unpredictable as in humans.

Avalanche formation in multiwire proportional or drift chambers can be considered as a microplasma discharge. In the plasma of an electron avalanche, chamber gases, vapour additions and possible contaminants are partially decomposed, with the consequence that aggressive radicals may be formed (molecule fragments). These *free radicals* can then form long chains of molecules, i.e., *polymerisation* can set in. These polymers may be attached to the electrodes of the wire chamber, thereby reducing the gas amplification for a fixed applied voltage: the chamber ages. After a certain amount of charge deposited on the anodes or cathodes, the chamber properties deteriorate so much that the detector can no longer be used for accurate measurements (e.g. energy-loss measurements for particle identification).

Ageing phenomena represent serious problems for the uses of gaseous detectors especially in *harsh radiation environments*, such as at future high-intensity experiments at the Large Hadron Collider at CERN. It is not only that gas mixtures for detectors have to be properly chosen, also all other components and construction materials of the detector systems have to be selected for extraordinary radiation hardness.

https://doi.org/10.1017/9781009401531.015 Published online by Cambridge University Press

Which processes are of importance now for the premature ageing of gaseous detectors, and which steps can be taken to increase the lifetime of the chambers?

Ageing processes are very complex. Different experimental results concerning the question of ageing are extremely difficult to compare, since ageing phenomena depend on a large number of parameters and each experiment usually has different sets of parameters. Nevertheless, some clear conclusions can be drawn even though a detailed understanding of ageing processes has yet to come. The main parameters which are related to wire-chamber ageing are characterised below [1–13].

A multiwire proportional chamber, drift chamber or more general gaseous detector is typically filled with a mixture of a noble gas and one or several vapour additions. *Contaminants*, which are present in the chamber gas or enter it by outgassing of detector components, cannot be completely avoided. The electron avalanche, which forms in such a gas environment in the immediate vicinity of the anode structure, produces a large number of molecules. The energy required for the break-up of covalent molecule bonds is typically a factor of three lower than the ionisation potential. If electrons or photons from the avalanche break up a gas molecule bond, radicals that normally have quite a large dipole moment are formed. Because of the large electric field strength in the vicinity of the electrodes, these radicals are attracted mainly by the anode and may form in the course of time a poorly or non-conducting *anode coating*, which can cause the electrodes to be noisy. Conducting anode deposits increase the anode diameter, thereby reducing the gas amplification. Because of the relatively large chemical activity of radicals, different compounds can be produced on the anode in this way. The rate of polymerisation is expected to be proportional to the density of radicals which in itself is proportional to the electron density in the avalanche. Polymerisation effects, therefore, will increase with increasing charge deposition on the anode. However, not only the anode is affected. In the course of polymer formation (e.g. positive) polymers may be formed which migrate slowly to the cathode. This is confirmed by patterns of 'wire shadows' which can be formed by deposits on planar cathodes [1, 2].

Typical deposits consist of carbon, thin oxide layers or silicon compounds. Thin metal oxide layers are extremely photosensitive. If such layers are formed on cathodes, even low-energy photons can free electrons from the cathodes via the photoelectric effect. These photoelectrons are gas amplified thus increasing the charge deposition on the anode, thereby accelerating the ageing process. Deposits on the electrodes can even be caused during the construction of the chamber, e.g. by finger prints. Also the gases which are used, even at high purity, can be contaminated in the course of the manufacturing process by very small oil droplets or silicon

dust (SiO_2). Such contaminants at the level of several ppm can cause significant ageing effects.

Once a coating on the electrodes has been formed by deposition, high electric fields between the deposit layer and the electrode can be produced by secondary electron emission from the electrode coating (*Malter effect* [14]). As a consequence of this, these strong electric fields may cause field-electron emission from the electrodes, thereby reducing the lifetime of the chamber.

Which are now the most sensitive parameters that cause ageing or accelerate ageing, and which precautions have to be considered for chamber construction? In addition, it is an interesting question whether there are means to clean up (*rejuvenate*) aged wires.

Generally, it can be assumed that pure gases free of any contaminants will delay ageing effects. The gases should be as resistant as possible to polymerisation. It only makes sense, however, to use ultrapure gases if it can be guaranteed that contamination by outgassing of chamber materials or gas pipes into the detector volume can be prevented.

These precautions are particularly important for the harsh environments at high-intensity colliders where long-term operation with limited access to the detectors is foreseen. The gaseous detectors must be able to withstand particle fluences of up to 10^{15}–$10^{16}\,\mathrm{cm}^{-2}$ and charge deposits on chamber wires of $\approx 1\,\mathrm{C/cm}$ per year.

In standard multiwire proportional chambers this margin can be reached with certain gas mixtures and carefully designed chambers

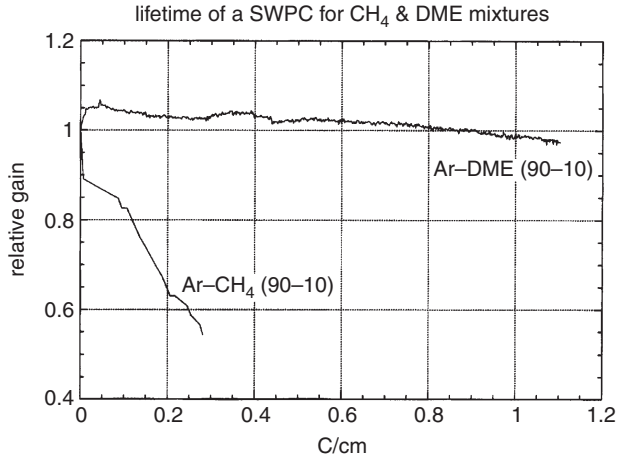

Fig. 12.1. Comparison of the gain variation of a clean single-wire proportional chamber filled with argon–methane or argon–dimethyl ether under irradiation [15].

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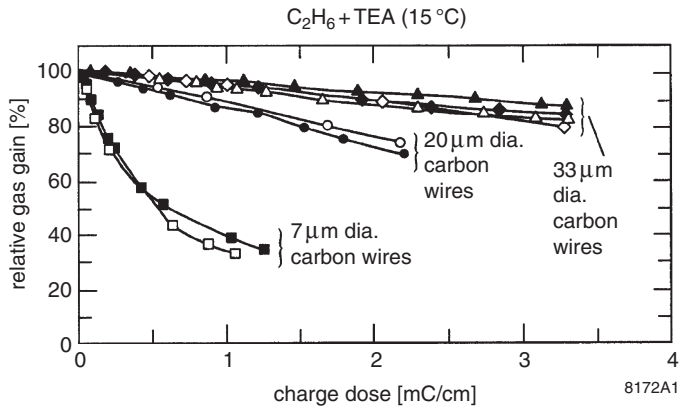

Fig. 12.2. Wire-chamber ageing in multiwire proportional chambers filled with C_2H_6 + TEA for different anode-wire diameters as a function of the deposited charge on the anode [16].

constructed of selected materials. Figure 12.1 shows the gain variation of a clean single-wire proportional chamber under irradiation for two different gas mixtures [15]. While the gain loss in standard argon–methane mixtures (90:10) is substantial already after 0.2 C/cm, an argon–dimethyl-ether ($(CH_3)_2O$) filling (90:10) loses less than 10% in gain after an accumulated charge of 1 C/cm.

Figure 12.2 shows the ageing properties of a multiwire proportional chamber filled with a mixture of ethane (C_2H_6) and the photosensitive gas TEA (triethylamine, $(C_2H_5)_3N$) often used for the detection of Cherenkov photons in gaseous ring-imaging Cherenkov counters (RICH) [16]. The gain change correlates with the diameter of the anode wire, which is not a surprise because depositions have the largest effect for low-diameter wires. Already for charge doses as low as 1 mC/cm anode wire significant gain losses are experienced.

Figure 12.3 shows a comparison between TEA and TMAE (Tetrakis-dimethylamino ethylene, $[(CH_3)_2N]_2C = C[N(CH_3)_2]_2$) for a wire diameter of 20 µm [16]. The ageing rate with TMAE is considerably faster than that with TEA. Electrode coatings observed in TMAE can also induce the Malter effect, as indicated in the figure. Detectors of this type can only be used in gaseous Cherenkov counters in relatively low radiation environments.

Apart from multiwire proportional and drift chambers, micropattern detectors or gas electron multipliers can also be used. Here it is not only important to reduce ageing effects such as gain losses, but also to maintain best spatial resolution and best timing properties.

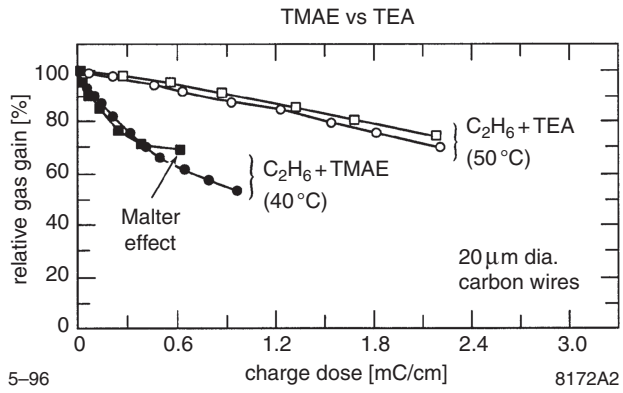

Fig. 12.3. Comparison of wire-chamber ageing in multiwire proportional chambers filled with C_2H_6+TEA versus C_2H_6+TMAE for a fixed anode-wire diameter in its dependence on the deposited charge on the anode wire [16].

Naturally, prototype detectors are tested for ageing under laboratory conditions with X rays, γ rays or electrons. In addition, there is also experience of ageing from low-rate colliders, such as from the Large Electron–Positron collider LEP at CERN. The detectors operated under these conditions may not function in high-intensity beams of hadrons where the ionisation densities can exceed those obtained with electrons by a large margin (up to 100 times of minimum-ionising particles). Especially α particles and nuclear recoils with high Z and low velocities lead to huge charge densities which might initiate streamer or even spark formation. High intensities will also create *space-charge effects*, which are sure to lead to gain losses.

Sparks are particularly dangerous because they can cause local damage to the electrodes which might introduce low-resistivity channels thereby leading the way for further discharges. This is because local enhancements of the field are formed at the edges of the imperfections on the electrodes created by the spark.

Gases of interest for high-rate applications are, e.g., Ar(Xe)/CO_2 or Ar(Xe)/CO_2/O_2. CF_4 mixtures also show little ageing, but CF_4 is quite aggressive and limits the choice of construction materials for detectors and gas systems. Under high irradiation the CF_4 molecule might be decomposed thereby creating fluorine radicals and hydrofluoric acid (HF) which might attack the chamber body (Al, Cu, glass, G-10, etc.). There is no final proof that CF_4 is a reliable chamber gas for harsh radiation environments. To be on the safer side, hydrocarbons should be avoided.

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For the expensive xenon-based gas mixtures in large detector systems one is forced to use recirculation systems where special purification elements are required to remove long-lived radicals. Also cleaning runs with Ar/CO_2 might be helpful.

Apart from undesired contaminants, additions of atomic or molecular oxygen and/or water may take a positive influence on ageing phenomena.

Special care has to be taken for possible *silicon contaminants*. Silicon – as one of the most frequently occurring elements on Earth – is contained in many materials which are used for chamber construction (like G-10 (glass fibre–reinforced epoxy resin), various oils, lubricants, rubber and adhesives, grease, O-rings, molecular sieves) and in dust. Silicon is frequently contained in gas bottles in the form of silane (SiH_4) or tetrafluorsilane (SiF_4). Silicon can, together with hydrocarbon contaminants, form silicon carbide; this, together with oxygen silicates, which have – because of their high mass – a low volatility and almost are impossible to remove from the chamber volume, will be preferentially deposited on the electrodes.

Apart from avoiding unfavourable contaminants in the chamber gas, and by carefully selecting components for chamber construction and the gas system, some constructional features can also be recommended to suppress ageing affects.

Larger cathode surfaces normally have smaller electric fields at their surface compared to layers of cathode wires. Therefore, continuous cathodes have a reduced tendency for deposition compared to cathode wires. The effect of deposits on thin anode wires is quite obviously enhanced compared to thick anode wires. Also careful selection of the electrode material can be of major influence on the lifetime of the chamber. Gold-plated tungsten wires are quite resistant against contaminants, while wires of high-resistance material (Ni/Cr/Al/Cu alloys) tend to react with contaminants or their derivatives, and this may lead to drastic ageing effects.

Certain contaminants and deposits can be dissolved at least partially by additions of, e.g., water vapour or acetone. Macroscopic deposits on wires can be 'burnt off' by deliberately causing sparks. On the other hand, sparking may also lead to the formation of carbon fibres (*whiskers*) which significantly reduce the lifetime of chambers, and can even induce wire breaking.

Figure 12.4 shows some examples of deposits on anode wires [3]. On the one hand, one can see more or less continuous anode coatings which may alter the surface resistance of the anode. On the other hand, also hair-like polymerisation structures are visible which will decisively deteriorate the field quality in the vicinity of the anode wire and also may lead to sparking.

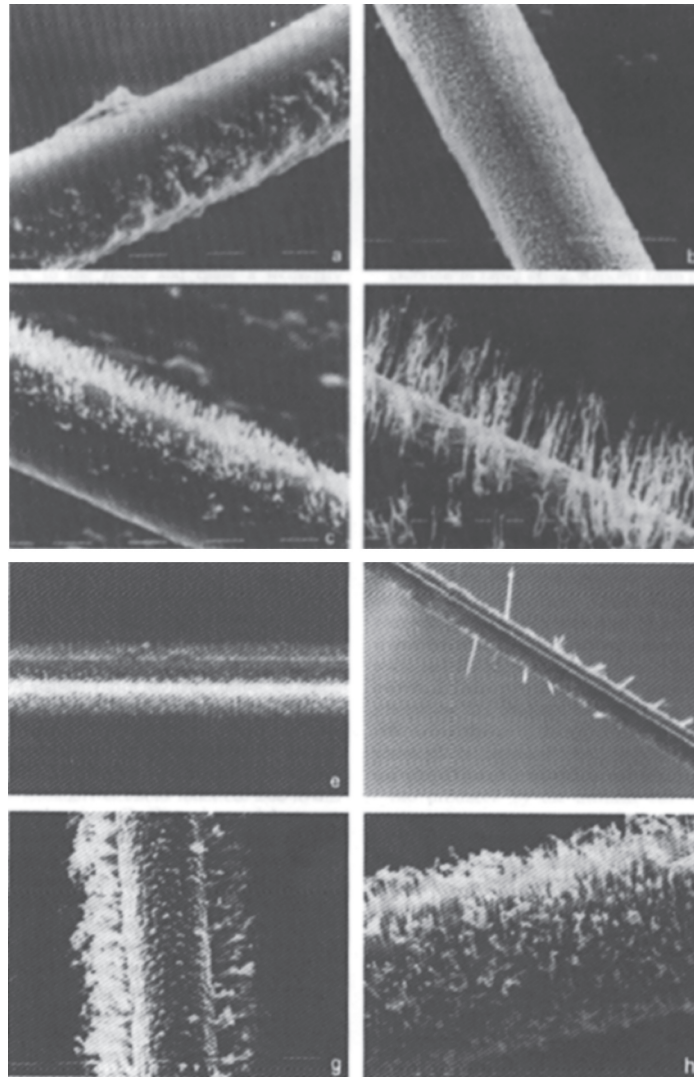

Fig. 12.4. Examples of depositions on anode wires [3].

12.2 Radiation hardness of scintillators

Scintillators, Cherenkov media, wavelength shifters and readout fibres are susceptible to degradation due to both natural ageing and radiation effects. High radiation fields will reduce the light output and transmission of the transparent media. If scintillators are used in calorimeters as sampling element, non-uniformities of response might be created as a consequence of non-uniform irradiation. Light losses and

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reduction in *transparency* will increase the constant term in the relative energy resolution, in particular, for hadron calorimeters in harsh radiation environments.

A possible radiation damage is also sensitive to details of the detector construction (choice of the scintillator material and the thickness of the scintillator plates) and its operation characteristics (e.g. selection of the wavelength to be used). It also makes a difference whether the scintillator sheets are sealed in vacuum or exposed to air (oxygen). Tests of radiation hardness with X rays, γ rays or electrons may not give conclusive information of the behaviour in high-radiation environments of hadrons or heavily ionising particles. It is also problematic to extrapolate from a short-term irradiation test with high doses to long-term operation with comparable doses but moderate dose rates.

At high absorbed doses plastic scintillators suffer a deterioration of both light output and transparency. This effect is poorly understood but usually ascribed to the creation of colour centres caused by the radiation. Since the transparency decreases, the total light output reduction of the scintillator depends strongly on the counter size and shape. Samples of the popular scintillators, BC-408, BC-404 and EJ-200 of 6 cm length, were studied in [17]. A light output decrease of 10%–14% was found after 600 Gy (60 krad) of absorbed dose. For a large number of new and known scintillators the damage under γ irradiation was studied in detail in [18]. The well-known NE-110 polyvinyltoluene scintillator retained about 60% of the initial light output at an absorbed dose of 34 kGy (3.4 Mrad). The deterioration effect strongly depends on the chemical composition of the material. The best scintillators based on polystyrene kept 70%–80% of light output after absorption of 100 kGy (10 Mrad). However, a noticeable transparency deterioration was observed already at 2–3 kGy (200–300 krad).

It should be noted that the radiation damage does not only depend on the total absorbed dose but from the dose rate as well. A certain recovery of the light output was observed after several weeks for some scintillators.

The radiation tolerance of inorganic scintillation crystals used in electromagnetic calorimeters (see Chap. 8) varies within a wide range [19]. The main radiation-induced effect is a transparency reduction exhibiting a strong dependence of the output signal on the shape and size of the counter. It should be noted that a partial recovery some time after irradiation is observed for some of the materials.

Widely used alkali-halide crystals, e.g. CsI and NaI, have a moderate radiation resistance [20, 21]. A typical dose dependence of the light output for several CsI(Tl) crystals of 30 cm length is presented in Fig. 12.5 [21]. These crystals can be used up to several tens of Gray (a few krad) of absorbed dose which is usually sufficient for low-energy experiments.

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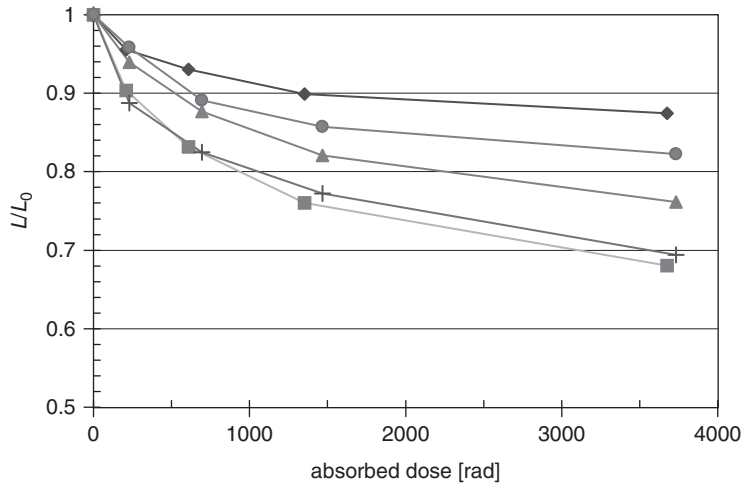

Fig. 12.5. Relative light output, L/L_0, in its dependence on the absorbed dose for several crystals of 30 cm length [21].

Some of the oxide scintillation crystals show a much improved radiation resistance. It was reported [22, 23] that BGO crystals grown according to a special technology can be used under γ radiation up to 0.8–1 MGy (80–100 Mrad) of absorbed dose. Lead-tungstate crystals will be used in the CMS electromagnetic calorimeter [24] at an expected absorbed dose of up to 10 kGy (1 Mrad) per year.

In contrast to solid detector materials, liquid scintillators have shown excellent levels of radiation resistance. This can be due to the fact that *dislocations* caused by impacts of heavily ionising particles are more easily repaired in liquids.

12.3 Radiation hardness of Cherenkov counters

For Cherenkov media in general – apart from the global reduction of transparency under irradiation – also the change of the frequency-dependent transparency resulting in a modification of the average effective index of refraction, and the introduction of non-uniformities can degrade the performance of this type of detector significantly.

As an example, lead glass, frequently used for calorimeters, loses transparency up to a considerable extent at an absorbed dose of several tens of Gy (several krad). However, cerium admixtures improve the radiation hardness substantially, and cerium-doped glasses can withstand an irradiation up to 100 Gy (10 krad) [25].

To build a Cherenkov detector of high radiation resistance one can use quartz as radiator. Tests of the prototype of the CMS hadronic forward calorimeter using quartz fibres embedded into an iron absorber showed that an absorbed dose of 1 MGy (100 Mrad) induces an additional light attenuation of about 30% per m at a wavelength of 450 nm [26].

12.4 Radiation hardness of silicon detectors

The performance of silicon detectors depends also on the radiation environment. Heavily ionising particles or neutrons may displace atoms in the silicon lattice producing *interstitials* and thereby affecting their function. Strongly ionising particles will deposit a large amount of charge locally thus producing space-charge effects. This can also happen when energetic hadrons generate nuclear recoils by nuclear reactions within the silicon detector.

The radiation damage in silicon can be subdivided into bulk and surface damage. The displacement effect in the bulk leads to increased *leakage currents*. Charge carriers produced by the signal particles can be trapped in these defects and space charge can build up which might require to change the operating voltage. If sufficient energy is transferred to recoil atoms, they can generate dislocations themselves thus creating dislocation clusters.

Radiation damage at the surface can lead to charge build-up in the surface layers with the consequence of increased surface currents. In silicon pixel detectors also the interpixel isolation is affected.

Bulk damage leads to an increase in the reverse-bias current. Since this is strongly temperature-dependent, even a modest cooling can reduce this effect. Due to the build-up of space charge in the detector, the required operating voltage to collect the generated signal charge drops initially with fluence until the positive and negative space charges balance. At large fluences the negative space charge starts to dominate and the required operating voltage increases. Silicon pixel or strip detectors can stand applied voltages up to ≈ 500 V.

A radiation-induced increase of the reverse current of many types of silicon devices is presented in Fig. 12.6 as a function of the radiation intensity equivalent to 1 MeV neutrons, Φ_{eq} [27, 28]. This dependence can be expressed by the simple equation

$$I\{\mathrm{A}\} = \alpha \cdot \Phi_{\mathrm{eq}}\{\mathrm{cm}^{-2}\}\, V\{\mathrm{cm}^3\}\ , \tag{12.1}$$

where $\alpha = (3.99 \pm 0.03) \times 10^{-17}\,\mathrm{A\,cm}$, when the silicon device has undergone a certain annealing after irradiation.

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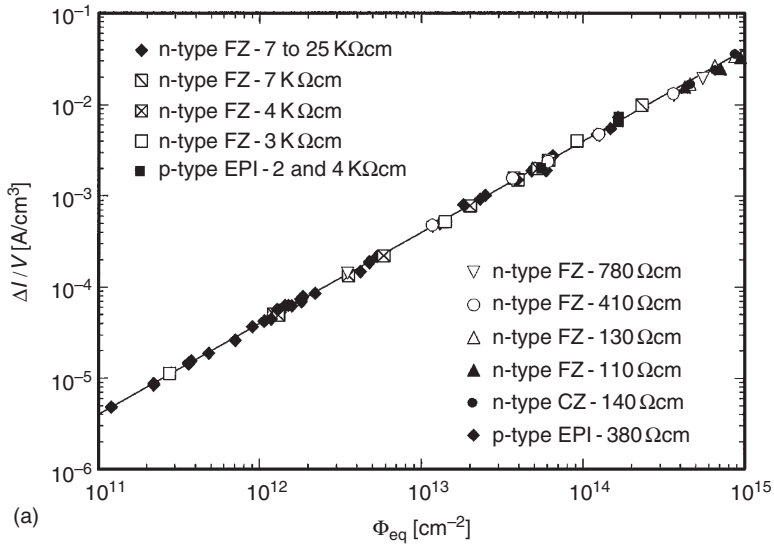

Fig. 12.6. Reverse current of different silicon detectors produced by various technologies induced by the exposition to an equivalent fluence Φ_{eq}. The measurements were performed after a heat treatment for 80 min at 60 °C [28].

The mobility of defects in silicon can be substantially suppressed by strong cooling. On the other hand, additions of oxygen have the effect of 'capturing' vacancies in the silicon lattice and it could also capture interstitials. These *oxygenated silicon detectors* – even at fairly moderate cooling – are significantly radiation harder compared to standard silicon devices without additions of oxygen [29].

It has to be mentioned that the radiation damage of a silicon detector, as seen in an increase in leakage current, effective doping change or the creation of trapped states, decreases with time after the end of the irradiation. This 'improvement' of the properties of the damage in silicon detectors depends critically on the temperature at which the counter is stored. This partial disappearance of the radiation damage has been called 'annealing'. The crystal may even become perfect again, for example, if the vacancies created by irradiation are filled in again by silicon interstitials. Frequently, the defects may also be transformed to more stable defect types which may have less harmful properties [30]. The term 'annealing' already indicates that the defects are in general quite stable up to a certain temperature. They may disappear if a given 'annealing temperature' is exceeded. The characteristic properties of such defects can be reduced at higher temperatures, and this may even happen over a very extended period of up to a year after the irradiation has ended. The details of the annealing process appear to be rather complicated and poorly understood.

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On the other hand, silicon detectors can also be trained to tolerate high radiation levels. The idea of this *radiation hardening* is to use techniques that result in silicon material whose properties are not significantly altered when they are exposed to radiation. To achieve this, different approaches can be followed: stable defects can be created by controlled doping or by the design of radiation-tolerant device structures of the silicon material.

When trying to improve the radiation hardness of silicon detectors, one has always to keep in mind that the associated readout electronics, often integrated onto the silicon chip, is exposed in the same way to the radiation as the detector. Therefore, in designing a radiation-hard silicon detector, both aspects, the detector and the readout, have to be considered together.

For silicon detectors and readout components used in a harsh radiation environment in locations where they are not easily accessible, like in the running of LHC experiments, sufficient safety factors have to be foreseen to guarantee the proper functioning of the devices [31, 32].

12.5 Problems

12.1 Defects produced by irradiation decrease in the quiet phase after irradiation according to

$$N_{\mathrm{d}}(t) = N_{\mathrm{d}}(0)\,\mathrm{e}^{-t/\tau} \ ,$$

where the decay time τ depends on the activation energy E_{a} and on the annealing temperature T like

$$\tau(T) = \tau_0\,\mathrm{e}^{E_{\mathrm{a}}/kT} \ .$$

In room-temperature annealing the decay time can easily be one year ($E_{\mathrm{a}} = 0.4\,\mathrm{eV}$, $kT = 1/40\,\mathrm{eV}$). If the annealing time should be reduced to one month, by how much should the ambient temperature be increased?

12.2 The electron signal in a proportional tube is given by

$$\Delta U^{-} = -\frac{N\,e}{C\ln(r_{\mathrm{a}}/r_{\mathrm{i}})}\ln(r_0/r_{\mathrm{i}}) \ ,$$

where r_0 is the position, where the charge has been created, and $r_{\mathrm{a}}, r_{\mathrm{i}}$ are the outer radius of the counter and the anode-wire radius, respectively ($r_{\mathrm{a}}/r_{\mathrm{i}} = 100$, $r_0/r_{\mathrm{i}} = 2$). Work out the gain loss if the anode-wire diameter is increased by 10% due to a conductive deposition.

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