SHAPING OF p-i-n DETECTOR PULSES BY RC NETWORKS

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Abstract

In this paper are presented :

a : the results of pulse shape calculations for particles incident perpendicular to the p-type surface of a lithium drifted junction detector ;

b : the non-linearities introduced by shaping these pulses with a single RC integrator followed by a single RC differentiator ; the time constants of the networks are equal and have the same order of magnitude as the pulse rise time.

1. Introduction

In the study of nuclear reactions the semiconductor junction detector is nowadays extensively used, because of its excellent energy resolution. The energy resolution which can be achieved with these detectors is limited by the noise generated in the detector and associated electronics. In practice networks, with a suitably designed frequency characteristic, are used to obtain the optimal signal to noise ratio.

In the case of the p-i-n junction, or lithium ion drifted, detector the main contribution to the noise is usually shot noise due to the detector current. This noise source gives rise to a noise voltage with a $1/f$ frequency distribution. To minimize this noise, networks with short time constants are required. On the other hand the pulses obtained from p-i-n junction detectors are generally relatively slow. The pulse rise times, which may be as long as several microseconds, can not be considered to be small in comparison with the time constants of the shaping networks. This means that also the detector pulses may be attenuated considerably. The design of networks for optimal signal to noise ratio is complicated by this

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fact. Moreover, the amplitude of the shaped pulse becomes dependent on the shape of the detector pulse. Since the shape of the detector pulse is a complex function of the energy non-linearities are introduced.

In this paper the shaping effect of the combination of a single RC integrating and a single RC differentiating network is considered. The pulse attenuation and shape dependent distortion are calculated. No attention is given to noise reduction and optimalization of the signal to noise ratio.

2. Input pulse

The subject of pulse shape analysis of *p-i-n* detector pulses has been treated in detail in a previous paper (*). The lines along

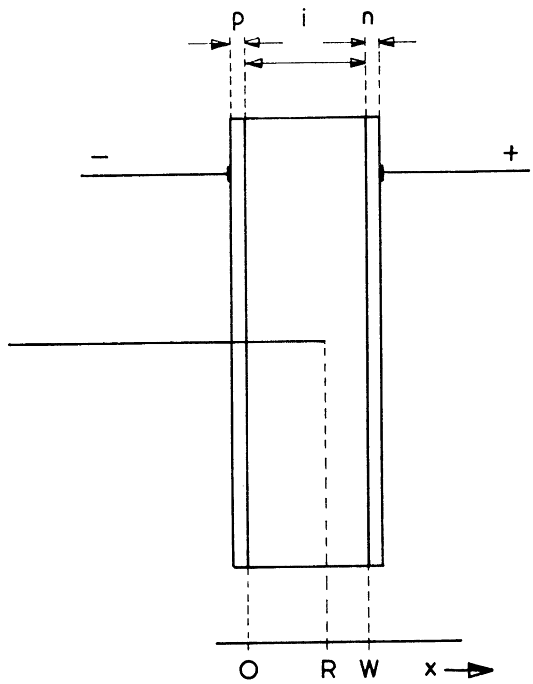

Fig. 1. — Representation of the detector and the incident particle.

(*) C. A. J. Ammerlaan, R. F. Rumphorst, L. A. Ch. Koerts, *Nuclear Instruments and Methods*, **22** (1963), 189.

which this analysis proceeds will be summarized in this chapter and the results will be given.

The detector is a window-less *p-i-n* detector made by the lithium ion drift process. In the ion drift process an intrinsic region, thickness W, has been created between a *p*- and *n*-type layer. In the reverse biased detector, reverse voltage V, there is a homogeneous electric field in the intrinsic region of magnitude V/W. Particles with energy E_i are incident upon this detector, perpendicular to the *p*-type surface. Their range in silicon is given by R. The situation is illustrated by figure 1. An empirical range-energy relationship of the type $R = a.E_i^b$ is used ; a and b are parameters which are adjusted to give a best fit with the experimental data. For all types of particles the value $b = 1.73$ has been chosen. The particles lose their energy in the semiconductor material primarily by electronic excitation, i. e. the creation of free electrons and holes. The density of the electrons and holes along the particle track is proportional to the specific energy loss. In the intrinsic region the electrons and holes are separated by the electric field. The electrons, which have a drift mobility μ_e, will move with velocity $\mu_e.V/W$. The electron transit time $t_{t,e}$ is therefore given by $t_{t,e} = W^2/\mu_e.V$. The hole mobility μ_h is assumed to be a factor three smaller than the electron mobility : $\mu_h = \mu_e/3$. The motion of electrons and holes induces a voltage pulse on the detector electrodes. The shape of the pulse is obtained by summing the contributions of all electrons and holes. The pulse height at time t is given by $E(t)$. The maximal pulse height is equal to the energy loss of the particle in the intrinsic region of the detector.

The pulse shape formula are expressed in reduced quantities. These quantities and their definitions are :

reduced range $\rho = R/W$

reduced time $\tau = t/t_{t,e}$

reduced pulse height $\varepsilon = E(t)/E_i$.

The results in mathematical form are then :

for $0 \leqslant \rho \leqslant 1$ and $0 \leqslant \tau \leqslant 1 - \rho$ and $0 \leqslant \tau \leqslant 3 . \rho$:

$$\varepsilon = \tau + \frac{b . \rho}{b+1} \left\{ 1 - \left(1 - \frac{\tau}{3 . \rho}\right)^{\frac{b+1}{b}} \right\}$$

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for $0 \leqslant \rho \leqslant 1$ and $1 - \rho \leqslant \tau \leqslant 1$ and $0 \leqslant \tau \leqslant 3 . \rho$:

$$\varepsilon = \tau + \frac{b . \rho}{b+1} \left\{ 1 - \left(1 - \frac{\tau}{3 . \rho}\right)^{\frac{b+1}{b}} - \left(1 - \frac{1 - \tau}{\rho}\right)^{\frac{b+1}{b}} \right\}$$

for $0 \leqslant \rho \leqslant 1$ and $1 - \rho \leqslant \tau \leqslant 1$ and $3 . \rho \leqslant \tau$:

$$\varepsilon = \tau + \frac{b . \rho}{b+1} \left\{ 1 - \left(1 - \frac{1 - \tau}{\rho}\right)^{\frac{b+1}{b}} \right\}$$

for $0 \leqslant \rho \leqslant 1$ and $1 \leqslant \tau$ and $0 \leqslant \tau \leqslant 3 . \rho$:

$$\varepsilon = 1 - \frac{b . \rho}{b+1} \left(1 - \frac{\tau}{3 . \rho}\right)^{\frac{b+1}{b}}$$

for $0 \leqslant \rho \leqslant 1$ and $1 \leqslant \tau$ and $3 . \rho \leqslant \tau$:

$$\varepsilon = 1$$

for $1 \leqslant \rho$ and $0 \leqslant \tau \leqslant 1$:

$$\varepsilon = \tau - \frac{\tau}{3}\left(1 - \frac{1}{\rho}\right)^{\frac{1}{b}} + \frac{b . \rho}{b+1} \left\{ 1 + \left(1 - \frac{1}{\rho}\right)^{\frac{b+1}{b}} - \left(1 - \frac{1-\tau}{\rho}\right)^{\frac{b+1}{b}} - \left(1 - \frac{\tau}{3 . \rho}\right)^{\frac{b+1}{b}} \right\}$$

for $1 \leqslant \rho$ and $1 \leqslant \tau \leqslant 3$:

$$\varepsilon = 1 - \frac{\tau}{3}\left(1 - \frac{1}{\rho}\right)^{\frac{1}{b}} + \frac{b . \rho}{b+1} \left\{ \left(1 - \frac{1}{\rho}\right)^{\frac{b+1}{b}} - \left(1 - \frac{\tau}{3 . \rho}\right)^{\frac{b+1}{b}} \right\}$$

for $1 \leqslant \rho$ and $3 \leqslant \tau$:

$$\varepsilon = 1 - \left(1 - \frac{1}{\rho}\right)^{\frac{1}{b}}.$$

The results in graphical form are presented in figure 2.

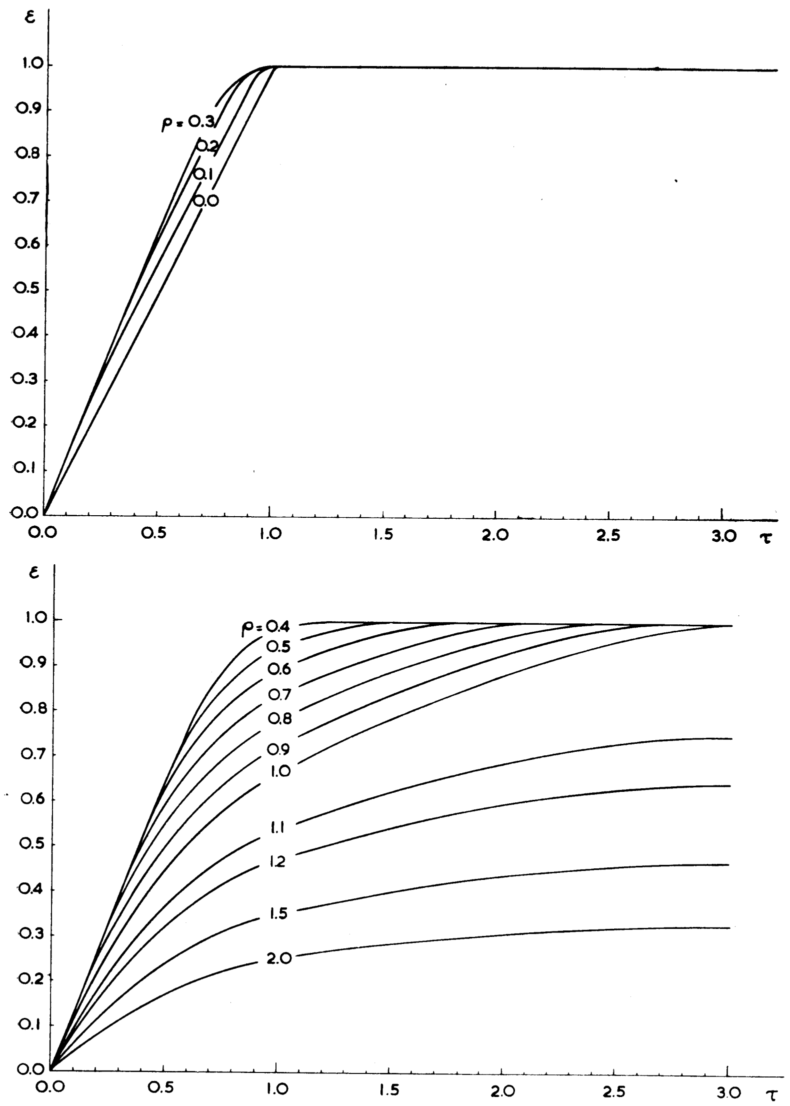

Fig. 2. — Pulse shapes for radiation incident perpendicular to the p-side of a p-i-n detector. The curves are labelled with the appropriate value of the reduced range.

3. Shaping network

The shaping network consists of a single RC integrator followed by a single RC differentiator. The network is shown in figure 3.

It is often used because of its simplicity and its good properties from the point of view of signal to noise ratio. The time constants of the networks t_{RC} are chosen to be equal : $t_{RC} = R_i.C_i = R_d.C_d$. The reduced time constant τ_{RC} is defined by $\tau_{RC} = t_{RC}/t_{t,e}$. The detector pulses are the input pulses for the shaping network and are denoted by V_i ; the shaped detector pulses or output pulses are denoted by V_u.

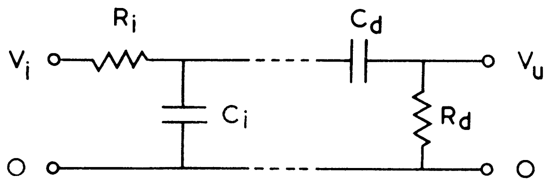

Fig. 3. — The pulse shaping network.

4. Output pulse

In the case of fast pulses the exact shape of the input pulse is not reflected in the shape and amplitude of the output pulse. The input pulse therefore may be put equal to a step function : $V_i(\tau) = H(\tau)$. The output pulse is obtained as the exact solution of differential equations ; the result is :

$$V_u(\tau) = \tau/\tau_{RC}.\exp(-\tau/\tau_{RC}).$$

This pulse reaches its maximum at $\tau = \tau_{RC}$; the maximal value is $1/e$. An illustration is given in figure 4, upper part.

The assumption of fast pulses is not satisfied in the case of *p-i-n* detector pulses. A more general approach is required therefore. The input or detector pulses may be written as a superposition of step functions :

$$V_i(\tau) = \varepsilon(\tau) = \int_0^{\tau} \frac{d\varepsilon(\tau')}{d\tau'}.H(\tau - \tau').d\tau'.$$

The network described in the previous chapter is a linear network. The ouput pulse is therefore given by the same superposition of step response functions :

$$V_u(\tau) = \int_0^{\tau} \frac{d\varepsilon(\tau')}{d\tau'}.\frac{\tau - \tau'}{\tau_{RC}}.\ \exp\left(-\frac{\tau - \tau'}{\tau_{RC}}\right).d\tau'.$$

The output pulse is slower, because always $\tau_{max} > \tau_{RC}$, and has also smaller amplitude. This is illustrated in figure 4, lower part, for the case $\rho = 1$, $\tau_{RC} = 1$.

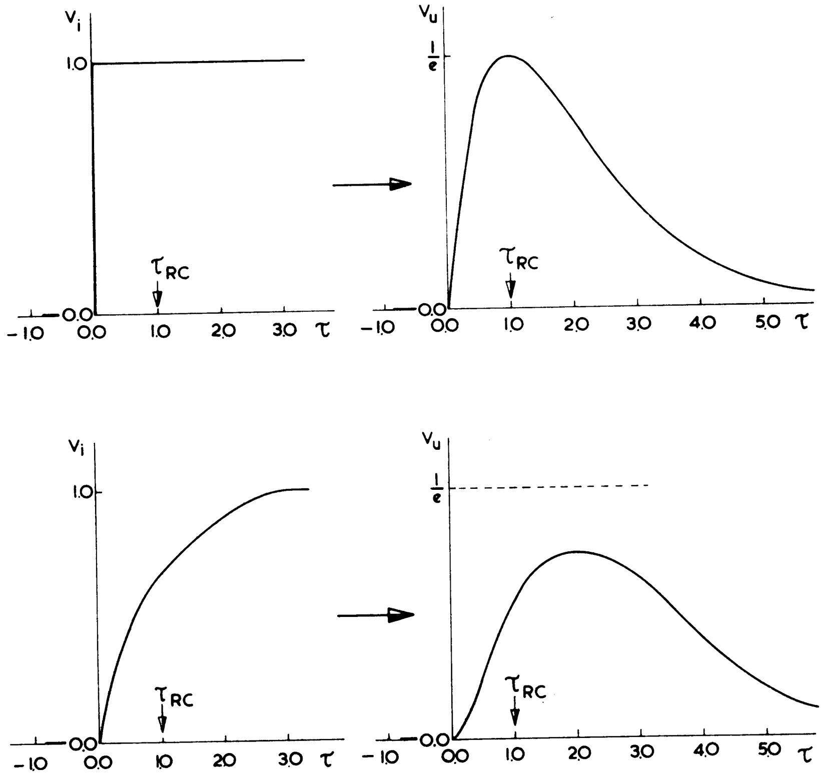

Fig. 4.

Upper part : the step function and step response function.

Lower part : the detector pulse for $\rho = 1$ and the shaped detector pulse for $\tau_{RC} = 1$.

The maximal value of the output pulse can be written as :

$$V_{u,\,max} = 1/e.\ S(\rho,\tau_{RC}) \qquad \text{for } 0 \leqslant \rho \leqslant 1$$

and $$V_{u,\,max} = 1/e\{1 - (1 - 1/\rho)^{1/b}\}.\ S(\rho,\tau_{RC}) \quad \text{for } 1 \leqslant \rho$$

The attenuation is described by the factor S, which is less than one. By defining this factor in the above mentioned way, S contains only the shape dependent attenuation. The pulse shape is determined by the range, which in its turn is given by the energy, mass and charge of the incident particle. Since S is thus energy dependent, the output signal is no longer proportional to the energy of the incident particle. These non-linearities are also described by the factor S. The non-linearity for a given value of shaping time constant is measured by the maximum over the minimum value of S.

Numerical values of S were calculated as function of ρ and τ_{RC}. The results are presented in figure 5.

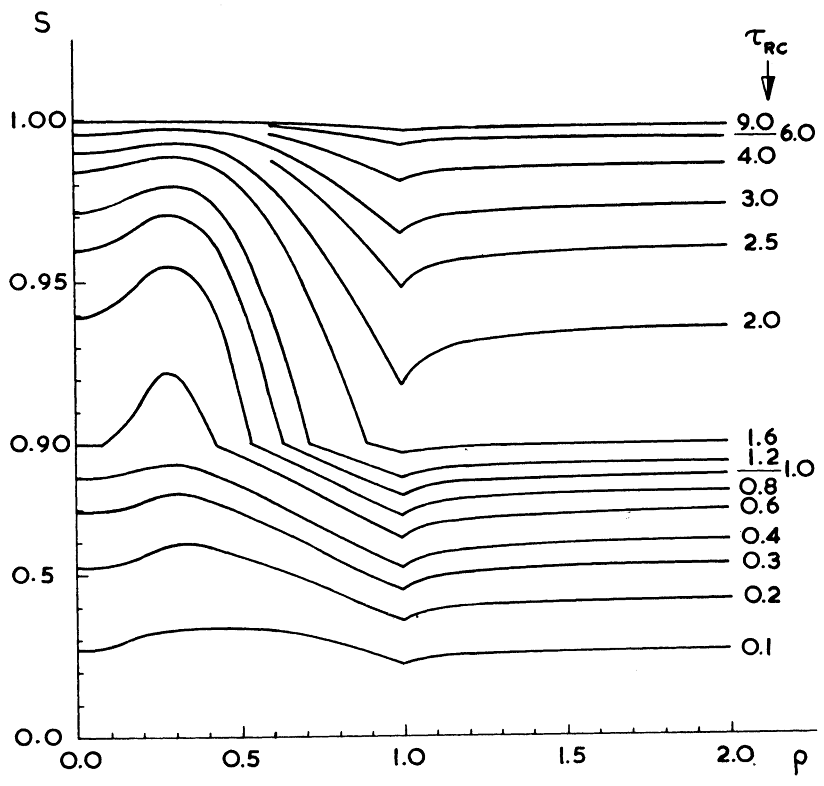

Fig. 5. — The attenuation factor S as function of the reduced range ρ and the shaping time constant τ_{RC}. Note change of scale at S = 0.90.

5. Discussion of the results

The amount of non-linearity can be determined from the data presented in figure 5. For $\tau_{RC} = 1$, which means pulse shaping time equal to the electron transit time, the non-linearity is 1.31. Other values for the non-linearity are : 1.10 at $\tau_{RC} = 1.8$; 1.01 at $\tau_{RC} = 5.5$; 1.003 at $\tau_{RC} = 9$.

The information given in figure 5 enables a detailed calculation of the distortion of the energy scale. This is of help in the analysis of complex spectra, where an exact knowledge of peak positions is required.

Knowledge of the effect of shaping networks on the detector pulses forms part of the solution of the more general problem of signal to noise optimalization.

Particle identification is possible by comparing the range and energy dependent RC shaped pulses with delay line clipped pulses, which may easily be made only energy dependent.

The numerical results on which figure 5 is based are available on request for a slightly wider range of the parameters. Calculations for particles incident perpendicular to the *n*-type surface of a *p-i-n* detector are in progress.

Acknowledgments

The calculations have been carried out on the computer X1 of the Mathematical Centre in Amsterdam. The construction of a computer program was largely due to the efforts of Mr. H. L. Jonkers. The interest of Dr. R. van Lieshout in the work on semiconductor detectors is very much appreciated.

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Question of M. SVELTO to M. AMMERLAAN. — I would like to add a brief comment to that paper. The calculations of the amplitudes of the output pulses for different energies in Li-drifted counters, have been done with fixed bandwidth of the amplifier, limited by two RC = 1 μsec. But, when there is a problem of finite rise time (charge collection time in the μsec range) it is more useful to utilize a delay line shaping network, with only an integration time constant ; the advantages are : limited ballistic deficit, good resolution and resolving time.

Reply of M. AMMERLAAN to M. SVELTO. — I agree with the comment that M. Svelto made. Actually we use delay line clipping in connection with the *p-i-n* detector work in our Institute. In this way we indeed obtain proportionality between pulse height and particle energy, good energy resolution and high allowed counting rate. However, it is not an easy task to maintain sufficient zero balance during the long decay times of only slightly differentiated pulses.