**The energy response dependence of a silicon sampling calorimeter on the
silicon depleted layer width**

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Abstract: The dependence of the energy response of a silicon sampling calorimeter on the depletion depth of silicon detectors has been studied with tungsten as absorber and for incoming electrons with an energy of 4 GeV. The detectors were operated with depletion depths of 40, 70, 100, 125, 150 and 200 μm (by adjusting the reverse bias voltage). The total deposited energy varies linearly with the depleted layer width. However at large depths (greater than 18 radiation lengths), where the deposited energy is small compared to the total energy, a deviation from linearity is observed.

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1. Introduction

Silicon detectors are currently employed as a major high precision instrument in nuclear and high energy physics [1], where their high resolution, fast transit time, and ability to operate in magnetic fields and vacuum and under geometric constraints are greatly appreciated. The application of silicon counters in calorimetry has only recently begun [2]-[4], following the development of large area detectors of low resistivity which can successfully operate undepleted (not fully depleted) [2]. Since the geometric volume occupied by a calorimeter is often large, using detectors with as large an area as possible lowers the number of electronic channels, thereby reducing costs and relative calibration problems. In addition, the use of low resistivity silicon reduces material costs, and operating the detectors undepleted better defines the active layer, and allows lower bias voltages to be applied, resulting in smaller leakage currents.

In a previous paper [5] we have presented the first results of a silicon sampling calorimeter operated with depletion layers of 200 and 70 μm . This paper presents the experimental results of a more detailed and systematic study of the longitudinal shower development in a silicon sampling calorimeter as a function of the depleted layer width of its silicon counters.

2. The experiment

The detectors under reverse bias behave as large capacitors, with a depletion depth inversely proportional to the capacitance per unit area. Since the diode junction at the surface of each detector is, to a very good approximation, a step junction, capacitance per unit area, C_T , is related to the reverse bias voltage, V , by [2]

$$C_T \approx 1.958 \cdot 10^4 / \sqrt{\rho[V+V_B]} \quad [\text{pFcm}^{-2}] \quad (1).$$

In the above equation the intrinsic, or 'built-in', voltage, V_B , depends on the silicon resistivity. Thus, the depletion depth can be controlled by adjusting the reverse bias voltage applied to the detectors.

As preparation for the experiment, each detector was studied to determine the dependence of its capacitance on reverse bias voltage. We employed an HP 4192A LF impedance analyser to measure the capacitance of each detector at various bias voltages between 1 and 35 V. The meter

oscillator strength was set at 10 mV and its frequency at 10 kHz. The data points were then fitted by the method of least squares to the straight line functional form of equation 1. The results allow the determination of the bias voltage corresponding to any required capacitance, in particular for thin depleted layers.

Fig 1 shows the capacitance vs voltage curves for a low resistivity detector selected for the experiment. The fit results are superimposed on the data.

The experiment was performed in the t_9 beam at the CERN-PS. In order to have some overlap with published data, we chose tungsten as absorber for the calorimeter and an incoming electron beam with an energy of 4 GeV. We used exactly the same beam and calorimeter configurations as our previously reported 200 and 70 μm depletion depth results [4], [5]. The calorimeter contained 24 radiation lengths of tungsten, with a silicon detector located after each two radiation lengths of absorber. Each detector was placed in the calorimeter so that the junction side faced the beam. A helium gas Cherenkov counter was used to identify electrons. A coincidence between the Cherenkov and a beam particle traversing a square scintillator of 0.25 cm^2 area ensured that only electrons triggered the electronics, and that the triggering electrons would shower centered in the calorimeter, thus containing the shower laterally.

The calorimeter calibration also proceeded exactly as previously. Before taking data we set the detectors at 200 μm depletion, and equalized the electronics using α 's from an Am^{241} [4], which have a range of about 40 μm in silicon. The calibration signal in the detectors from the α particles is independent of the depletion depth; however, the gain of the pre-amplifiers is strongly dependent on capacitance of the detectors at large capacitance values. This is demonstrated in Fig 2, where the calibration signal pulse height from a detector is plotted as a function of its depletion depth. Also shown is the relative gain of the preamplifier as a function of the corresponding detector capacitance. Since the two curves match well, we concluded that we need only to correct for changes in preamplifier gain with depletion depth.

Each silicon detector was read out individually to its own ADC channel. An on-line sum was also performed in order to obtain directly the overall energy response.

We took data with the detectors set at six depletion depths:

$$X_D = 40, 70, 100, 125, 150, 200 \text{ } \mu\text{m}.$$

Before taking data for a given X_D , there was also a short pedestal run. As we expected, the pedestals were stable to better than 0.6 % during the data taking. After cuts to remove hadrons and multiple electron events, our data sample consisted of 15000 events almost equally shared among the six depletion depth runs.

3. Data analysis

Fig 3 presents the longitudinal shower transition curves for each of the six depletion depths. The 200 and 70 μm data are in good agreement with our previously published results. The data show a clear two component structure. The first component, at depths in the calorimeter less than about 18 radiation lengths, is similar to what has been observed in other experiments and in Monte Carlo studies (see [4]). The second, new component in the shower tail whose prominence increases with increasing depletion depths, becomes very evident at 200 μm . The peak position of the transition curve is independent of the depletion depth and averages 5.54 ± 0.14 radiation lengths; however, the measured median shower position, t_{med} , increases linearly with X_D (table 1). If the deposited energy at all depths were strictly proportional to the depleted layer width, one would expect t_{med} to be independent of X_D .

Fig 4 shows the overall energy response of the calorimeter as a function of depletion depth. As is seen from the figure, the response is linear over the whole range measured. Noteworthy is the positive energy intercept of the line. Because of charge diffusion in the silicon (the migration effect [6]), one expects to always collect some charge from the field-free region closest to the junction, even when the external applied bias voltage is zero. Each detector then has an effective active layer consisting of the charge depletion region due to the intrinsic 'built-in' voltage V_B and the diffusion field-free zone. This would lead one to predict a positive intercept to the energy response curve. From the fitted slope and intercept of the line we find an average effective contribution from the field-free region, X_{FF} , of $23 \pm 2 \text{ } \mu\text{m}$, at zero depletion depth. This should be compared with value of 25 μm found by Croituru, Rancoita, and Seidman [6], who worked with similar shaping time constant of electronics, but under

non-showering conditions with relativistic β^- particles from a source which were detected in a single silicon counter.

The energy response of the individual counters is plotted in fig. 5. The lines are a least squared fit to the data. The detectors divide themselves naturally into four groups: (a) the first two detectors in the rise of the shower transition, (b) the three detectors near the peak, (c) the next detectors in the first component fall off, and (d) the last four detectors in the second component. Except for group (d), the response of the individual detectors is quite similar to the overall response, i.e. a linear dependence of the deposited energy versus the depleted layer width. Table 2 gives the average contribution from the field-free region. for the groups (a), (b), and (c). In addition, the slopes are expected to be proportional to the number of equivalent minimum ionizing particles traversing the detectors. Therefore, the slopes should increase monotonically until the shower maximum and decrease monotonically thereafter. This is the behaviour observed.

The response of group (d) is highly nonlinear, and shows a rapid growth in deposited energy at large values of depletion depth. The curves shown are hand drawn to guide the eye. The effect exhibited is possibly due to soft electrons depositing a large amount of energy near the end of their range. However the deposited energy in these detectors is small compared to the overall deposited energy in the calorimeter and does not affect the linear calorimeter response versus the depleted layer width X_D .

4. Conclusions

The behaviour of a silicon sampling calorimeter as a function of depleted layer width is in agreement with the response expected from the simplest model of a silicon diode junction and electromagnetic shower development. Early in the shower, the energy deposited grows linearly with depletion depth, the energy in each counter being proportional to the number of ionizing particles traversing it. The detectors have an effective sensitive layer due to the built-in voltage and charge migration from the field-free region, so that they are active even at no externally applied bias voltage.

At depths in the calorimeter greater than about 18 radiation lengths significant deviations from the expected linear behaviour are observed. At such depths a new component to the shower transition curves appears.

This component becomes more marked with growing depletion depth due to a rapid increase in deposited energy. Since the energy deposited in the final detectors is small compared to the total energy, the overall response of the calorimeter versus the depleted layer widths continues to be linear.

Table 1:

Depleted layer width, X_D , vs median shower position t_{med}

$X_D[\mu\text{m}]$	40	70	100	125	150	200
t_{med}	7.35	7.57	7.73	7.78	7.88	8.17
Δt_{med}	± 0.22	± 0.22	± 0.21	± 0.21	± 0.21	± 0.21

Table 2:

Contribution from field-free region

Detector Group	(a)	(b)	(c)
$X_{FF}[\mu\text{m}]$	25 ± 4	34 ± 4	6 ± 2

References

- [1] P.G.Rancoita and A.Seidman, *La Rivista del Nuovo Cimento*, Vol.5 N.7 (1982)
- [2] G.Barbiellini, P.Buksh, G.Cecchet, J.Y.Hemery, F.Lemeilleur, P.G.Rancoita, G.Vismara and A.Seidman, *Nucl.Instr. and Meth. A* 235 (1985), 216
- [3] A.Nakamoto, H.Murakami, T.Doke, J.Kikuchi, K.Masuda, K.Kasahara, K.Mitsui, Y.Muraki and T.Yuda, A Si(Li)-Pb shower calorimeter for p-p collider experiments, ICR-Report-118-84-7 (November 1984)
- [4] G.Barbiellini, G.Cecchet, J.Y.Hemery, F.Lemeilleur, C.Leroy, G.Levman, P.G.Rancoita and A.Seidman, *Nucl.Instr. and Meth. A* 235 (1985), 55
- [5] G.Barbiellini, G.Cecchet, J.Y.Hemery, F.Lemeilleur, C.Leroy, G.Levman, P.G.Rancoita and A.Seidman, Electromagnetic shower development in uranium and tungsten: a comparison of data from a silicon sampling calorimeter, CERN-EP/84-157 (November 1984), and *Nucl.Instr. and Meth. A* in press
- [6] N.Croituru, P.G.Rancoita and A.Seidman, *Nucl.Instr. and Meth. A* 234 (1985), 443

FIGURE CAPTIONS

Fig 1 : Plot of capacitance, C , versus bias voltage, V , for silicon detector NB10 which was located at a depth of 22 radiation lengths in the detector. The line shows (eq. 1) the result of least squared fit to the data. From the fit results we determine that $\rho = 1.51 \pm .01$ k Ω -cm, and that $V_B = 1.4 \pm .4$ V . The fit χ^2 was 13.

Fig 2 : Plot of calibration signal pulse height (●) from detector NB31 versus depletion depth. Also shown is the relative gain of the preamplifier as a function of the corresponding input capacitance (full line).

Fig 3 : The longitudinal shower development in the silicon/tungsten sampling calorimeter for the depletion depths of $X_D = 40, 70, 100, 125, 150,$ and 200 μm . The curves superimposed on the figure show the results of a linearized least squares fit to the data. The fitting procedure is described in [4].

Fig 4 : The energy response of the calorimeter as a whole as a function of the silicon detector depletion depths X_D . The line shown is a least squared fit to the data.

Fig 5 : The energy response of the individual silicon detectors as a function of depletion depths; (a) the first two detectors at depths of 2, and 4 radiation lengths in the calorimeter; (b) the next three detectors at depths of 6, 8, and 10 radiation lengths, respectively; (c) the next three at depths of 12, 14, and 16; and finally (d) the last four silicon detectors located 18, 20, 22, and 24 radiation lengths into the calorimeter.