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EXPERIMENTAL RESULTS FROM SILICON SAMPLING CALORIMETER

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Abstract: Investigations of longitudinal electromagnetic shower development in calorimeters consisting of sandwiches of Si/W and Si/U are described. Also results of a study of the dependence of the energy response of a silicon sampling calorimeter on the depletion depths of the silicon detectors, with tungsten as an absorber, are presented.

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1. Introduction

Electromagnetic calorimeter capabilities replace or supplement information obtained with magnetic spectrometers. Electromagnetic calorimeters are sensitive to both charged and neutral particles, have a short response time permitting high particle rates and since their response is different to electrons, muons and hadrons it may enable particle identification. They have also other intrinsic properties which make them advantageous.

Recently the signal in sampling calorimeters is being measured by thin silicon detectors offering good localization of showers at room temperature. Using a high-Z converter like tungsten (W) or uranium (U), interspaced with about 300 μ m thick silicon detectors, a calorimeter with very high effective radiation length can be built. Because of high energies involved, sandwich calorimeters seem to be a logical choice for experiments at colliders.

The usage of silicon detectors in electromagnetic calorimetry was made possible by the development of inexpensive large-area detectors of low resistivity which can operate not fully depleted[1]. These sandwich calorimeters seem to be the right choice for the future colliding beam machines such as the e^+e^- LEP and SLC and the ep HERA where calorimeters should possess very good energy resolution for both electrons and hadron jets.

In order to find out to what extent the silicon sampling electromagnetic calorimeters answers the many requirements, longitudinal shower development of electrons was investigated[2]. Also the dependence on depletion depth of the energy response of a silicon sampling calorimeter was studied[3].

2. Radiation Damage

The effects of radiation damage on ion-implanted silicon junction detectors employed in electromagnetic calorimeters were investigated [4],[5].

It was found that irradiation of ion-implanted silicon detectors is accompanied by an increase in leakage current[6]. This can be explained by the fact that an increased generation-regeneration bulk current is caused by radiation-induced centers in the depletion region. It was found that the leakage current is sensitive to the gradient of the irradiation. The

radiation-induced increase in leakage current is roughly proportional to the increase of the fluence. The leakage current does not remain constant with time.

Another conclusion: the layer width of a fully depleted detector (before irradiation) becomes smaller and dependent on temperature after irradiation. It was found that this degradation of performance with irradiation is smaller for detectors with lower resistivity. Degraded energy resolution is caused by trapping centers (generated by irradiation) which remove charge from the pulse within the amplifier shaping time. The trapping centers and reduction in carrier mobility, increase the rise time of the output pulse.

3. Longitudinal Shower Development and Energy Resolution

Longitudinal electromagnetic shower development was investigated in a silicon sampling (sandwich) calorimeter with uranium and tungsten absorbers and with silicon detectors operated with depleted layer widths of 70 and 200 μ m. The calorimeter contained 24 radiation lengths of either uranium or tungsten. Data were taken with incoming electron energies of 2, 4 and 6 GeV (from CERN-PS).

The two-component structure of the longitudinal shower development can be parametrized[2],[7]:

$$\epsilon = \epsilon_0 (t/2)^a \exp(-bt) + \epsilon_1 (t/2)^c \exp(-m(t-x_1)-y_1) \quad [\text{MeV}]$$

where ϵ is the deposited energy as a function of t , t is the depth of the passive material in radiation lengths, ϵ_0 and ϵ are normalization constants proportional to the depleted layer width, a , b , c , m , x_1 and y_1 are dimensionless parameters which vary logarithmically with the number of [GeV]s of the incident energy E :

$$a=a'+a'' \ln E, \quad b=b'+b'' \ln E, \quad c=c'' \ln E, \quad m=m'' \ln E, \quad x_1=x_1'+x_1'' \ln E.$$

The parameters a and b are in approximate agreement for all data set. Thus, for t smaller than 14, the shape of the longitudinal shower development does not depend on either the absorber, uranium or tungsten, or the depletion layer width[2]. At depths larger than 18, a second component is present in the shower decay. This component depends on both the absorber

type and silicon detector depletion width.

Fig.1 shows the energy response of the calorimeter as a function of the incoming electron energy. The linearity is observed for the detectors operated with depleted layer widths of 200 and 70 μm , and employing both uranium and tungsten as showering media. The mean detected energy with uranium is about 11% higher than with tungsten.

The energy resolution is about $17.6\% \sqrt{\tau/E}$ (where τ is the sampling frequency) by using detectors operated with depletion layer width of 200 μm [7] and is degraded by no more than 10-15% with depleted layer width of 70 μm [2].

4. Energy Response Dependence on the Depletion Depths

The dependence of the energy response of a silicon sampling calorimeter with tungsten as absorber on the depletion depths of the silicon detectors was studied for an incoming electron beam with an energy of 4 GeV [3]. As already mentioned, the calorimeter contained 24 radiation lengths of tungsten, with a silicon detector after each 2 radiation lengths. The response of the detector located at depths of 2 to 16 radiation lengths was found to be a linear dependence of the deposited energy on the depleted layer width, whilst for those located at 18 to 24 radiation lengths depth (fig. 2), the dependence is highly nonlinear and shows a rapid growth in deposited energy at large values of depletion depth, where the shower contains mainly electrons and photons below the critical energy. However, it does not affect the linear calorimeter response as a function of the depleted layer width, since the deposited energy in those detectors is small compared to the overall deposited energy in the calorimeter.

Fig. 3 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[8]), one expects to always collect some charge from the field-free region closest to the junction, even when the externally 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 of the line we find an average effective contribution from the

field-free region, X_{FF} , of $(23 \pm 2) \mu\text{m}$, at zero depletion depth. This should be compared with the value found by Croitoru, Rancoita and Seidman [8], who worked with similar shaping time constant 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. 4. 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 1 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 up to 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 .

5. Conclusions

The silicon sampling calorimeter is compact, fast, granular and is not affected by high magnetic fields. Its potential feature of high stability, enables absolute energy calibration of better than 1%.

The behaviour of a silicon sampling calorimeter as a function of depleted layer width is in good 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, 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 with no externally applied bias voltage.

The energy resolution was found to be comparable with that obtained with sampling calorimeters using liquid argon as active samplers.

The use of silicon detectors in hadronic calorimetry might allow the investigation of the extent to which the compensation mechanism is related to photons emitted in the fission process. The use of a hydrogenic material in front of the devices could also extend the investigation to the neutrons emitted during fission.

Table 1

Contribution from the field-free region

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

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Figure Captions

Fig.1 Mean energy detected by the calorimeter vs. the incoming electron energy for uranium with a silicon depletion layer of 200 μm (■); for uranium with a silicon depletion layer of 70 μm (□); for tungsten with a silicon depletion layer of 200 μm (●); for tungsten with a silicon depletion layer of 70 μm (○). The full lines are the least squares fits to the data.

Fig.2 The longitudinal shower development in the silicon/tungsten sampling calorimeter for depletion depths of 40, 70, 100, 125, 150 and 200 μm . The curves superimposed on the data show the results of a linearized least squares fit.

Fig.3 The energy response of the calorimeter as a whole as a function of the Si-detector depletion depths X_D . The line shown is a least squared fit of the data.

Fig.4 The energy response of the individual silicon detectors as a function of depletion depth; (a) the first two detectors at depths of 2, and 4 radiation lengths in the calorimeter; (b) the next three 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 at 18, 20, 22, and 24 radiation lengths into the calorimeter.

Fig 1

Fig 2

Fig 3

Fig 4a

Fig 4b

Fig 4c

Fig 4d