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DIRECT DETECTION OF VACUUM ULTRAVIOLET SCINTILLATIONS IN LIQUID HELIUM
USING GERMANIUM PHOTODIODES

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Direct detection of vacuum ultraviolet scintillations in liquid helium using germanium photodiodes

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Direct detection of vacuum ultraviolet scintillations in liquid helium produced by 5.3 MeV α particles has been accomplished using a high-purity germanium photodiode. The diode was immersed in the liquid helium and operated in the side-entry mode with a sensitive area of 0.3 cm x 1.0 cm. Scintillation from each α particle was detected as a single pulse. A signal rise time $< 0.1 \mu\text{sec}$ was obtained at an electric field $> 1200 \text{ Vcm}^{-1}$. The quantum efficiency of the photodiode was estimated to be ~ 4 .

The fact that liquid helium scintillates upon the passage of charged particles has long been established.^{1,2} Most of the luminescence photons have energies in the vacuum ultraviolet³ (VUV) and the spectrum consists of a broad peak centered around 800 Å corresponding to photon energy of ≈ 16 eV.^{4,5} Scintillation counters using liquid helium as the scintillator have found applications in various experiments.^{3,6,7} However, because the scintillations occur in a region of the VUV for which no window material with good transmission exists, their detection has relied upon the use of wavelength shifters to convert the photon into another spectral region (usually near UV or visible). The converted light is then collected and detected by photomultiplier tubes. Inefficiencies in the wavelength conversion process and in the collection of converted photons can cause a large decrease in the signal-to-noise ratio.

An alternative to such a detection scheme is to use a semiconductor photodiode immersed in liquid helium to directly detect the scintillation photons. To accomplish this requires a photodiode with a large sensitive area, high efficiency in the photon energy range of interest, preferably fast rise time for pulse detection and the ability to continuously operate at liquid helium temperature. Although no data exists on photodiodes with all of these properties, the sensitivity of large area silicon detectors in the VUV, operating at room temperature, has been measured.⁸ These detectors had thin (≈ 100 Å) Au Schottky barrier contacts and exhibited a quantum efficiency of ≈ 0.7 at 16 eV, increasing at higher photon energies. This value is approximately ten times lower than the intrinsic quantum efficiency of silicon measured by the same author.⁹ The low quantum efficiency of the detector was attributed to absorption of the VUV photons by the Au layer and Au-Si interface. A further important factor might be the increased recombination rate for electron-hole pairs at the contact. The electron-hole pairs are generated within only a few hundred Å from the surface because of the high absorption coefficient for VUV

photons. Similar effects related to surface recombination have been observed in semiconductor UV¹⁰ and low energy x-ray detectors.¹¹

In view of the unsatisfactory performance of room temperature operated silicon diodes, we have investigated the possibility of detecting scintillations in liquid helium using special high-purity germanium photodiodes operating in the side-entry mode (i.e. with illumination parallel to the diode junction). The use of side entry minimizes the recombination of electrons and holes at the surface because of the absence of a conductive layer. The electric field which is present near the surface enables fast separation and collection of the photocarriers. To obtain a thick depletion layer, i.e. a large sensitive area, we use high-purity germanium to fabricate the photodiode. In addition, the binding energies of electrons to donors or holes to acceptors in germanium are much lower than that of silicon. The use of germanium will therefore reduce the risk of trapping of photocarriers by the donor or acceptor impurities at liquid helium temperature.

The development of the photodiodes has been based on the technique developed for high-purity germanium nuclear radiation detectors.¹² For our VUV photodiodes we chose a 3 mm thick slice of single crystal germanium with a net donor concentration of $2.3 \times 10^{10} \text{ cm}^{-3}$. Full depletion is reached at a bias of 120 V. Because the dopant impurities in lightly doped germanium deionize at liquid helium temperature, we had to fabricate degenerately-doped contacts. A p^{++} and a n^{++} contact were formed on opposite sides of the germanium slice by ion implantation of boron ($2 \times 10^{14} \text{ cm}^{-2}$, 25 keV, 300 K) and phosphorus ($1 \times 10^{15} \text{ cm}^{-2}$, 25 keV, 77 K) respectively followed by thermal annealing at 330°C for 30 minutes.¹³ The slice was cut into 1 cm x 1 cm squares and the bare sides of each device were polish etched in a 7:2:1 mixture of HNO_3 :HF:red fuming HNO_3 for two minutes. Before testing, each device was given

a final side etching followed by quenching in methanol and by blowing dry with a nitrogen jet.

The experimental setup for testing the VUV photodiodes is shown schematically in Fig. 1. The diode was placed on a block of boron nitride mounted on a platform which is supported at the ends of two stainless steel tubes. Electrical connections to the contacts were made using indium pads. A ^{210}Po α source (5.3 MeV), used for generating the scintillations, was mounted near the photodiode. The distance between photodiode and source could be varied using an external mechanical linkage. The whole assembly could be lowered into a metal liquid helium dewar. Electrical leads from the photodiode were routed out of the dewar through the stainless steel tubes. One lead (n^{++} contact) was connected to a bias supply and the other (p^{++} contact) to a charge-sensitive preamplifier followed by a pulse shaping amplifier.¹⁴ A multichannel analyzer was used to obtain pulse height spectra of the signals.

The photodiode was immersed in liquid helium with the α source facing one of its sides. Special care was taken that no α particle could reach the detector by keeping the source at a distance greater than ten times the α range (~ 0.2 mm). Each signal pulse was then the sum contributions of a large number of VUV photons intercepted by the detector during one scintillation. The amplitude of the pulses depends on the solid angle subtended by the photodiode at the source. This could be varied by changing the diode-to-source distance. Spectra taken at three different distances ranging from ~ 4 mm to ~ 6 mm are shown in Fig. 2. The area under the peaks are equal to within a few percent in agreement with the idea that each α particle scintillation is detected, and that the amplitude is proportional to the solid angle. The widening of the pulse height distribution at short distances is attributed to the use of an extended α source (4 mm diameter) and the relatively small dimension of the sensitive area ($3 \times 10 \text{ mm}^2$) of the photodiode.

The peak at 60 keV is the gamma-ray line from an ^{241}Am source placed outside the dewar in the vicinity of the photodiode. This line serves as a calibration for determining the amount of charge collected in a pulse since it is known that an average energy of ≈ 3 eV is expended in creating an electron-hole pair in germanium.¹² The full-width-half-maximum (FWHM) of the peak is ≈ 3 keV which is dominated by electronic noise.

The signal rise time was measured indirectly using the ballistic deficit effect: if the rise time is comparable to or less than the shaping time, the amplitude of the processed signal will be lowered. With a reverse bias of 200 V, we have observed a drop of approximately 15% in the amplitude of the pulses when the shaping time was decreased from 4 μsec to 0.25 μsec but no decrease in amplitude could be observed with a reverse bias of 500 V. At low bias, part of the carriers were generated within low electric field regions of the photodiode leading to collection times of the order of 0.1 to 0.3 μsec . At sufficiently high bias, the electric field was increased to the point where collection times shorter than 0.1 μsec were obtained. The shortest possible rise time can be estimated from the depletion width of the photodiode (3 mm) and the saturation velocity of electrons and holes in germanium ($\approx 10^7$ cm sec⁻¹). It is ≈ 15 nsec for carriers generated near the middle of the depletion region.

The quantum efficiency of the photodiode, i.e. the number of electron-hole pairs collected for each photon impinging on the diode, can be calculated if we know the scintillation efficiency of liquid helium for the 5.3 MeV α particles, the solid angle subtended by the diode and the charge collected in each pulse. The solid angle can be calculated from geometric measurements and the amount of charge can be obtained by comparing the signal to that of the ^{241}Am 60 keV gamma-rays (Fig. 2). However, we were unable to find any reliable measurement of the scintillation efficiency of liquid helium for α particles. The scintillation efficiency for 160 keV electrons was found to be

$\sim 4 \times 10^{15}$ photons $\text{sec}^{-1} \mu\text{A}^{-1}$,⁴ corresponding to an energy conversion efficiency of $\sim 6\%$. Since other noble gases, in the gaseous¹⁵ and liquid phases,^{16,17} when used as scintillators behave linearly over wide ranges of particle energy and do not depend significantly on the type of particles, we expect the conversion efficiency of liquid helium for 5.3 MeV α particles to be approximately equal to that for 160 keV electrons. Using this assumption, we arrived at a quantum efficiency of ~ 4 for our photodiodes. This value can only be regarded as an order of magnitude estimate due to the uncertainties in our assumption and in the measured value of the scintillation efficiency for electrons. A greater than unity quantum efficiency is possible due to secondary ionizations by the energetic primary photocarriers. Similar effects gave rise to the high intrinsic quantum efficiency of silicon.⁹

The sensitivity of a photodiode which was exposed to room air for five hours and stored in a nitrogen atmosphere for ten days showed differences smaller than 8%.

The photodiodes used in this experiment have a relatively small sensitive area. Larger or multiple diodes can be used to increase sensitivity. Also, narrow strips of interlaced n^{++} and p^{++} contacts formed on the surface of a high purity germanium wafer will increase both the sensitive area and the electric field.

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FIGURE CAPTIONS

FIG. 1. Schematic diagram of the apparatus used for photodiode testing.

FIG. 2. Spectra taken at different source-to-photodiode distances with a bias of 150 V and a shaping time of 4 μ secs. (1) $d \approx 6$ mm. (2) $4 \text{ mm} < d < 6 \text{ mm}$. (3) $d \approx 4$ mm. The ^{241}Am gamma-ray line at 60 keV is used as a calibration.

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Figure 1.

Figure 2.

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