Super-sensitive avalanche silicon photodiode with surface transfer of charge carriers

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Abstract

New avalanche photodetector, combining properties of avalanche photodiode and charge coupled device was developed on the basis of MOSFET technology. The device employs the gain control and stabilization and is sensitive in visible and ultraviolet spectral regions. Experimental results with the new device are presented.

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PACS: 85.60.Dw; 29.40.–n; 87.58.Fg

Keywords: Avalanche; Photodiode; Detector; Photon detection

The avalanche photodiode (APD) is produced using standard MOSFET technology. One of the distinguishing features of the APD is surface transfer of charge carriers created in the avalanche process \cite{1,2}. The structure of its basic element is shown in Fig. 1. The APD consists of a semitransparent titanium layer (gate electrode 0.5 m m\textsuperscript{2}) separated from the semiconductor surface by a transparent to UV light silicon dioxide layer and a drift layer connected to the drain electrode to provide transfer of multiplied charge carriers along the Si–SiO\textsubscript{2} boundary. Avalanche multiplication of charge carriers, generated by photons, occurs in the p–n\textsuperscript{+} junction (under the gate electrode), where the breakdown potential is reduced due to additional ion implantation. The voltage applied to the APD is distributed between the depletion layer of the semiconductor and the SiO\textsubscript{2} layer. The charge carriers (holes), created in the avalanche process in a micro-region of the p–n\textsuperscript{+} junction, are collected in a small area at the Si–SiO\textsubscript{2} boundary, reducing the voltage drop in this micro-region. As a result, each elementary avalanche is self-quenched within a few nanoseconds due to this local negative feedback (LNF) effect. The holes drift from the avalanche region to the drain contact through a highly resistive drift layer during about 100 ns after the avalanche. The parameters (thickness and surface resistivity) of the drift layer are field dependent, and so the LNF effect and the APD gain can be controlled varying the gate potential.

Fig. 2 shows the photocurrent gain as a function of bias voltage applied to the drain electrode. It can be seen that character of the avalanche process...
in the APD is completely defined by the gate potential. At a fixed gate potential situation can be achieved when the gain becomes independent of the drain potential.

Fig. 3 shows the drain current $I_d$ vs. the source–drain voltage $U_{sd}$, which is one of the main characteristics of ordinary MOSFET transistor. Saturation-like character of the $I_d$ vs. $U_{sd}$ dependence is due to depletion of the $p^{+}$–Si source–drain channel and is achieved well below the operation voltage of the APD (~ 60 V). So the $p^{+}$–Si channel acts as an artificial controllable “resistive layer”.

Differential surface resistance of the source–drain channel as a function of the potential applied to the wafer base is shown in Fig. 4.

The ability to control the device operation varying the gate and the drain potentials makes it possible to create the novel multielement device — an avalanche charge coupled device (CCD) [2]. Intrinsic signal amplification is an alternative to the signal integration and would increase the CCD sensitivity and performance rate.

On the basis of the above discussed basic structure a large area ($2.7 \times 2.7$ mm$^2$) APD was produced. The sensitive area of this APD is surrounded by the continuous drain electrode, which is connected with the gate. Among other important properties of the APD are high quantum efficiency (QE) and low noise. Fig. 5 shows the quantum efficiency as a function of incident light wavelength. Excess noise factor $F \approx 5.8$ ($F/QE = 8.3$) was measured at a gain of $M \approx 10^4$ and a photon wavelength of $\lambda = 480$ nm. Noise was measured at 100 ns shaping time and was
found to be \( \sim 25 \) photons r.m.s. at room temperature \((25^\circ\text{C})\).

Fig. 6 shows performance of this APD coupled to an LSO scintillator \((4 \times 4 \times 10 \text{ mm}^3)\) as a \(\gamma\) radiation detector. The amplitude distribution was obtained using a \(^{137}\text{Cs}\) source. For comparison, a distribution obtained with the same scintillator crystal coupled to Hamamatsu R5600U PMT is shown. As it can be seen, the energy resolutions, obtained with the APD and PMT, are close in value (note that light collection in the APD was a half of that in the PMT).

As shown above, there is real possibility to develop on the basis of conventional MOSFET technology supersensitive large area APD, as well as avalanche CCD for detection of weak light pulses in visible and ultraviolet spectral regions.

References