ULTRAFAST SINGLE PHOTON DETECTOR WITH DOUBLE EPITAXIAL STRUCTURE FOR MINIMUM CARRIER DIFFUSION EFFECT

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Résumé. Photodiodes à avalanche spécifiquement projetées pour travailler avec tension de polarisation supérieure à la tension de breakdown sont employées pour détecter des photons isolés et mesurer leur temps d'arrivée avec résolution à picosecondes. La fonction de résolution temporelle de ces dispositifs (dénommés Single Photon Avalanche Diodes SPADs) est composée d'un pic étroit et d'une queue indésirable, due à diffusion de porteurs de charge. Nous avions précédemment projeté et fabriqué un dispositif avec une structure épitaxiale, qui avait réduit l'effet de diffusion à une brève queue de forme exponentielle, avec constante de temps 1.7 ns. En vue d'obtenir un ultérieur progrès, nous avons idéé et fabriqué une structure à double épitaxie. Les mesures effectuées avec ces dispositifs ont démontré une drastique réduction de l'effet de diffusion. La fonction de résolution est caractérisée par une largeur a mi-hauteur du pic de 45 ps et par une très brève queue exponentielle, avec constante de temps 270 ps.

Abstract. Avalanche photodiodes designed to work biased above the breakdown voltage are employed for timing single photons with picosecond resolution. The time resolution curve of these devices (called Single Photon Avalanche Diodes SPADs) shows a fast peak and an undesirable tail, due to carrier diffusion. We had, previously, designed an epitaxial SPAD structure that succeeded in reducing the effect to a short, exponential-like tail with 1.7 ns lifetime. In order to achieve a further improvement, we have devised and fabricated a double epitaxial structure. The measurements performed on these new devices show a drastic reduction of the diffusion effect. The time resolution curve of the new detector is characterized by a peak with better than 45 ps full-width at half-maximum (FWHM) and a short, exponential tail, with 270 ps lifetime.

I. INTRODUCTION

Single Photon Avalanche Diodes (SPADs) are used as ultrafast detectors in single photon counting techniques. They are p-n junctions with uniform breakdown voltage and low density of traps and generation centres in the depletion layer (1-8). The devices work biased above the breakdown voltage in the triggered avalanche mode. In this condition, the electric field at the active junction is high enough to sustain the flowing of an avalanche current. However, the device remains quiescent and the inverse current is practically zero until a carrier succeeds in triggering the avalanche. The current then rises to a detectable value; if the carrier is photogenerated, the leading edge of the avalanche current is synchronous with the arrival time of the photon. The self-sustaining avalanche current continues to flow until an external circuit quenches the diode by lowering the bias voltage close to or below the breakdown voltage. After a finite dead time, the working voltage of the device is finally restored, in order to make possible the detection and timing of another photon. The avalanche can also be triggered by carriers thermally generated or emitted from deep levels in the depletion layer of the active junction. The corresponding dark count rate must be minimized for avoiding impairment of the device performance. Careful processes are employed in the fabrication of the devices for minimizing the concentration of generation centres and deep levels in the depletion layer. In order to completely avoid the degradation of the device resolution due to the dark count rate, Cova and Longoni devised the active quenching method (6-8). By using active quenching circuits, SPADs can work in accurately controlled bias conditions and the dead time following each pulse can be made very short. Remarkable performance is thus achieved in various applications, such as optical fiber characterization, laser ranging, fluorescent decay analysis, etc. (8). The SPADs are, therefore, a solid state alternative to photomultiplier tubes, providing wider spectral sensitivity range, higher resolution in the measurement of the photon arrival time, low detector noise.

The time resolution curve of a single photon detector is given by the statistical distribution of the delay from the true arrival time to the actual detection time of the photon (6-10). It is measured in a time-correlated single photon counting set-up (10) employing picosecond optical pulses.

We had previously implemented and tested prototype SPAD devices, having the geometry described by Haitz (2). The active junction was formed by a shallow (0.3 μm) n+ layer in a p bulk substrate. A deep
diffused n+ guard ring surrounded it, avoiding edge breakdown. The resolution curve of the prototype SPAD devices is characterized by a peak and a slow tail. The fast peak is due to photons absorbed in the depletion layer and its width is mainly related to the statistical fluctuations in the avalanche build-up time. We observed and reported full-width at half-maximum (FWHM) values down to 60 ps (6–8). The experiments also showed that the time resolution improves by increasing the maximum electric field at the active junction (8). The tail is due to the minority carriers, photogenerated in the neutral region beneath the junction, that succeed in reaching the depletion layer by diffusion. Due to the wavelength dependence of the optical absorption coefficient, the intensity and the duration of the diffusion tail change with the wavelength of the detected photons. This effect represents a serious drawback to high resolution measurements of fast optical signals. In fact, the true signal waveform is obtained by a deconvolution analysis of the experimental data, which requires a very accurate knowledge of the shape of the resolution curve. In all cases where the optical signal is non-monochromatic, the actual resolution shape depends on the actual detected optical spectrum. Therefore, it may be impossible or at least impractical to obtain it with sufficient accuracy.

II. THE PREVIOUS EPITAXIAL STRUCTURE

In order to improve the time response of the detector, the diffusion tail must be reduced. Our approach was to design epitaxial device structures in which the substrate acted as a sink for photogenerated carriers and the active junction was located in a suitable epistate. A Monte Carlo program, previously developed in our laboratory (9), was used to compute the time-dependent diffusion effect in the devised structures and, consequently, to define the actual device design.

In Fig. 1, a schematic cross section of the previous single epitaxial structure is shown. The device was fabricated in a p epilayer over a n substrate (11). In this geometry the electrons photogenerated in the substrate cannot reach the epilayer. Furthermore, the reverse biased substrate–epilayer n–p junction competes with the active junction in collecting the electrons generated in the neutral p epilayer. The device structure is quite different from the previous non-epitaxial design, since the avalanche current flows now laterally to the side ohmic contact. The series resistance of the device depends, therefore, on the thickness of the epilayer beneath the guard ring. In order to avoid impairing the output signal, a few kOhm value should not be exceeded. This requirement sets a limit to the reduction of the epilayer thickness and, therefore, to the reduction of the diffusion effect. A shallow guard ring (2 μm) was, therefore, employed and a 12 μm thick epilayer was adopted. In order to achieve an improvement in the time resolution of the devices, the breakdown electric field was increased. A boron implantation increased the p doping in the active area, lowering the breakdown voltage down to 13 V. At the operative bias the maximum electric field attained values higher than 550 kV/cm.

The experiments fully confirmed the reduction of the diffusion tail, in excellent agreement with the Monte Carlo simulation. The tail is exponential-like and its lifetime is 1.7 ns. A remarkable improvement was also found in the peak FWHM. At 6 V excess bias, the device resolution is better than 30 ps at room temperature and 20 ps at -70 °C. To our knowledge, this is the highest time resolution so far reported in single-photon-timing measurements. It is worth noting, however, that the very high values of the maximum electric field employed entail a significant drawback. The dark count rate is strongly enhanced, due to the Frenkel-Poole effect and to the phonon-assisted tunneling effect, that enhance the carrier emission from generation centers and deep levels in the depletion layer (12). In fact, at room temperature the dark count rate of the devices was remarkably higher than that of the prototype SPADs, attaining several kpps already at 1 V excess bias and rapidly increasing with the bias voltage. Therefore, the high resolution of these SPADs can be fully exploited only by using active quenching arrangements.
III. THE DOUBLE EPITAXIAL STRUCTURE.

A further strong reduction of the diffusion tail requires to achieve a further reduction of the neutral epilayer thickness, but without increasing the series resistance beyond a few kOhms. The simple adoption of a thinner, higher-doped p epilayer would imply a marked reduction of the guard-ring breakdown voltage. The excess bias that could be applied to the active area would thus be reduced, and the output signal and the performance of the detector would correspondingly be impaired. We have, therefore, devised a new SPAD structure with two different p epilayers grown over the n substrate (Fig. 2). The buried epilayer, which is only 2 μm thick, provides a low resistivity path (0.3 Ohmcm) to the side contact. The active n+p junction is built in the upper, low-doped p epistrate (10 Ohmcm), which is only 2.5 μm thick. In order to reduce as far as possible the epilayer thickness, a different type of guard ring is used to dilute the electric field at the device periphery. Instead of using a deep n diffusion, a "virtual" guard ring structure is implemented: a boron implantation in the central part of the active junction defines the sensitive area of the detector. The low p doping in the outer part of the n+p junction and a field plate raise the edge breakdown voltage up to 50 V. Devices with this geometry have been fabricated with different diameters of the sensitive area, in the range from 8 to 20 μm. The boron implantation was deliberately made lighter than that used in the previous epitaxial devices, so that a slightly higher breakdown voltage was obtained, about 16 V. This limited the maximum electric field, thus avoiding the enhancement of the dark count rate at the cost of a slightly lower time resolution.

Fig.2 - Schematic cross section of the new, double epitaxial SPAD device.

Fig.3 - Optical pulse of a gain-switched laser diode (13) as measured in a time-correlated single-photon counting set-up with: a) the previous epitaxial SPAD; b) the new double epitaxial SPAD.
The experimental tests confirm the expected behaviour of the double epitaxial devices. Fig. 3a shows, in logarithmic scale, the pulse of a gain-switched laser-diode (13) measured using the previous epitaxial SPAD. As above mentioned, the diffusion tail has 1.7 ns lifetime. The peak width of 43 ps FWHM is due to the laser peak width (28 ps FWHM), to the detector time resolution (28 ps FWHM) and to the electronic noise and jitter (15 ps FWHM). The same measure performed with the double epitaxial SPAD is reported in Fig. 3b. It is characterized by a slightly larger peak width (55 ps FWHM) and by a much shorter diffusion tail. The actual value of the detector time resolution is 45 ps FWHM. It is evaluated by quadratically subtracting the 2E ps laser FWHM and the 15 ps electronic time jitter FWHM from the 55 ps FWHM of the experimental curve. The diffusion tail is exponential, with only 270 ps lifetime. In comparison to the previous epitaxial device, however, the initial tail intensity is higher. This behaviour is in agreement with the results of the Monte Carlo simulation. It can be intuitively explained, by taking into account the different geometry of the two devices. In the epitaxial device, the neutral region adjacent to the active junction had a longer, narrow tubular shape, with side walls acting as sinks for the diffusing carriers. In the new, double epitaxial device, the corresponding neutral region is thinner, but has a more open, almost planar shape. The carriers generated in close proximity to the active junction have, therefore, a higher probability of reaching it. These carriers contribute to the first part of the tail.

IV. CONCLUSIONS.

It can be concluded that the double epitaxial SPAD structure succeeds in producing a marked shortening of the diffusion tail. The physics of the phenomenon is well understood. The question naturally arises whether the tail can be further reduced or, better, completely eliminated. Work aiming to this goal is in progress in our laboratory. Anyhow, the high time resolution and the well-behaved, short diffusion tail of the device structures of a first-fabricated and reported make the Single Photon Avalanche Diodes an attractive solid-state alternative to photomultiplier tubes in all applications of the single-photon counting techniques that do not require large sensitive area detectors.

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