Spectral performance of FDDI and new proposed line codes are also presented for first time.

D. MUÑOZ-RODRIGUEZ
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J. B. AREVALO-GALARZA
Center for Research and Advanced Studies
Electrical Engineering Department
Apo. Postal 14-740
07000 Mexico, DF

References

STRONG DEPENDENCE OF TIME RESOLUTION ON DETECTOR DIAMETER IN SINGLE PHOTON AVALANCHE DIODES

Indexing terms: Avalanche diodes, Diodes

The fact that the time resolution of single photon avalanche diodes (SPADs) is mainly dependent on the size of the detector area is demonstrated. Larger the detector is, the worse the time resolution is. This result is related to the avalanche physics and sets the ultimate performance of these devices in single-photon timing.

Geiger-mode avalanche photodiodes are widely employed in single photon counting measurements of luminescence and fluorescence decays, characterisation of optical components and laser timing applications. These devices are essentially n-p junctions biased above the breakdown voltage, Vb. At the operating bias, the junction electric field is high enough to sustain the flow of an avalanche current. However, the diode current is zero until a carrier succeeds in triggering the avalanche. When the carrier is photogenerated, the leading edge of the avalanche current, sensed by a fast discriminator, marks the photon arrival time. The avalanche current flows until an external circuit quenches the diode, lowering the bias voltage below Vb. After a dead time, the bias is restored and the photodiode is ready to detect the arrival of another photon.

Commerically available avalanche photodiodes can detect the photon arrival time with a time resolution of 400 ps full width at half maximum (FWHM). However, values down to 20 ps FWHM were achieved with specifically designed devices, called single photon avalanche diodes (SPADs), fabricated with a shallow junction (±1 pm depletion layer width) and a diameter of 5 pm. The small detector area was considered up to now as a technological limit, which could be hopefully overcome in the future. This is not the case. Recently, we have demonstrated that the rise of the avalanche current is affected by the spread of the multiplication process from the point where the photon is absorbed to the whole active area. In this letter we show that this effect causes a strong dependence of the time resolution on the size of the detector area. We first explain how the avalanche propagation can influence the SPAD time resolution, and then we discuss the experimental data.

Fig. 1 schematically shows the active area of a circular device. When the avalanche is triggered, e.g. at P, the free carrier concentration around the seed point exponentially rises lowering the local electric field by the space charge effect. In a few tens of picoseconds, the electric field reaches the breakdown value, the multiplication process becomes self-sustaining and the carrier density around the seed point cannot increase further. However, by diffusion and multiplication of hot carriers, the avalanche is triggered in the surroundings of the activated area, i.e. the area where the multiplication occurs. We found that the avalanche spreads over the device junction with a constant speed v, only dependent on the device bias and given by

\[ v = kI \]

with k = 3 pm/(ns mA). As the activated area becomes larger, the diode current increases. Finally, when the avalanche multiplication occurs over the whole sensitive area the current reaches the final steady-state value I, given by the ratio between the excess bias, (V - Vb), and the diode series resistance Rb.

The rise of the diode current is dependent on the actual increase of the activated area. Therefore, in the circular device shown in Fig. 1, the leading edge of the current signal becomes steeper as the seed point moves from the periphery (point P) to the centre (point C). In fact the closer the seed point is to the centre, the faster is the activation of the whole sensitive area and the rise of the avalanche current to I,. As a consequence, the delay between the photon arrival and the detection of the current leading edge by a timing discriminator is dependent on the point where the photon is absorbed. Because the photons can be absorbed everywhere, the detector time resolution is limited by the difference between the times at which the fastest and the slowest leading edges cross the discriminator threshold. This difference increases by increasing the sensitive area and/or decreasing the propagation speed v. Therefore, the SPAD time resolution is expected to become worse as the sensitive area increases and/or I, decreases.

The time resolution of three silicon SPADs was measured in a conventional time-correlated single-photon counting set up using picosecond laser pulses. The devices have a shallow n-p junction (0.3 pm thick) obtained by phosphorus pre-deposition on a p-doped epilayer or substrate. In SPAD 1 and SPAD 2 the circular active area (8 pm 22 pm diameter, respectively) is defined by boron implantation in the centre of the n-p junction, and the lower p-doping at the junction.
edges raises the edge breakdown voltage at least 10 V above $V_b$. At room temperature, these devices have $V_b = 16$ V and their $R_s$ is 1.75 kΩ and 600 Ω, respectively. In SPAD 3, the sensitive area (10 μm diameter) is defined by a deep diffused (3 μm) phosphorus guard ring preventing the edge breakdown. At room temperature $V_b = 28$ V and $R_s = 1.3$ kΩ.

Fig. 2 shows the time resolution measured at room temperature and at $-65^\circ$C. Fig. 2a shows the data plotted against the excess bias ($V - V_b$) as usual in the literature.

**Note the dependence of the time resolution on the device diameter**

For a given excess bias, the time resolution of the smallest device is always the best. Moreover, the detector performance is improved by increasing the excess bias, cooling the device or focusing the light to a spot size (12 μm diameter in Fig. 2) less than the detector area. This result is a consequence of the avalanche propagation and the related effect on the current rise. At constant $I_p$, the time resolution is not dependent on the device temperature. In fact, the avalanche propagation is a hot carrier effect, $E_p$, and, more precisely, the value of $k$ in eqn. 1 is not expected to be strongly dependent on the lattice temperature. At constant excess bias, the decrease of the series resistance causes an increase of $I_p$ and $E_p$, improving the time resolution.

In conclusion, we have fully explained the dependence of SPAD time resolution on detector excess bias, temperature and sensitive area diameter. The reported results disclose the intrinsic limit of SPAD performance and make clear that the larger the detector the worse the time resolution. A trade-off between sensitive area and time resolution must be considered in SPAD design.

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A. LA CAITA
M. MASTRAPASQUA
Centro di Elettronica Quantistica e Strumentazione Elettronica—CNR and Politecnico di Milano
Dipartimento di Elettronica
Piazza L. da Vinci, 32, 20133 Milano, Italy

References


**'FIBRE/RADIO' FOR THE PROVISION OF CORDLESS/MOBILE TELEPHONY SERVICES IN THE ACCESS NETWORK**

A four channel CT2 fibre/radio system has been demonstrated over singlemode fibre using subcarrier multiplexing techniques. A spurious free electrical dynamic range of 51 dB was achieved which is sufficient for a mobile range of approximately 100 m. The use of subcarrier multiplexing simplifies the design of the radio transceiver and allows complex processing equipment to be located at the local exchange.

**Indexing terms**: Optical communication, Mobile radio systems

Introduction: The ability to deliver cordless/mobile services over a singlemode fibre network 1,2 potentially offers significant economic advantages. In particular, the use of subcarrier multiplexing (SCM) techniques over optical fibre offers advantages compared to copper or baseband optical systems for the provision of cordless or mobile telephony services. SCM allows the radio frequency (RF) carriers to be directly transported over the fibre between the radio distribution point (DP) and the local exchange without the need for frequency conversion and multiplexing/demultiplexing functions. Hence complex processing equipment can be located at the local exchange rather than the DP thereby simplifying field installation and maintenance procedures of equipment at the radio DP.

This letter reports on the first known demonstration of both single and four channel second generation cordless telephony systems (CT2),4 operating over an optical fibre link using SCM techniques. The optical system performance is described.