InGaAs/InP Single-Photon Avalanche Diodes show low dark counts and require moderate cooling

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ABSTRACT

InGaAs/InP devices suitable as Single-Photon Avalanche Diodes (SPADs) for photon counting and photon timing applications in the near-infrared provide good detection efficiency and low time jitter, together with fairly low dark-count rate at moderately low temperatures. However, their performance is still severely limited by the afterpulsing effect, caused by carriers trapped into deep levels during the avalanche current flow and later released.

We present preliminary experimental characterization of recently-developed InGaAs/InP detectors that can promisingly be operated slightly cooled. We investigate the primary dark-count rate, taking into account both thermal generation in the InGaAs absorption layer and trap-assisted tunnelling in the InP multiplication layer. We report on improvements obtainable by selecting the proper operating conditions and electronic circuit solutions. The fundamental role played by the front-end circuits in minimizing the effects of afterpulsing is assessed and demonstrated.

We report the performance of a 25 µm-diameter InGaAs/InP SPAD at 1550 nm wavelength, with dark count rate of 400 cps (count per seconds) at 175 K and just 2000 cps at 225 K, with afterpulsing showing off only below T_{OFF}=10µs. The photon timing resolution is 100 ps (FWHM, Full Width at Half Maximum) at 7 V of excess bias.

Keywords: Single Photon Counting, TCSPC, Photon Timing, Single Photon Detector, Active Quenching, Infrared Photons, Afterpulsing, Dark Count Rate, Time jitter.

1. INTRODUCTION

Single-photon detectors are the key device for many applications that require to measure faint near-infrared (NIR) light in the wavelength range between 1.0 and 1.7 µm. Quantum cryptography (Quantum Key Distribution, QKD) [1], eye-safe laser ranging (Light Detection And Ranging, LIDAR) [2], VLSI circuit characterization based on light emission from hot carriers in MOSFETs [3], singlet oxygen detection for dosimetry in photodynamic therapy (PDT) [4], time-resolved spectroscopy, etc. require single photon detectors with high quantum efficiency, low noise and low time jitter for the wavelength range above 1 µm.

The main detectors that satisfy such requirements are PhotoMultiplier Tubes (PMT), Superconducting Single-Photon Detectors (SSPD), and Single-Photon Avalanche Diodes (SPAD).

PhotoMultiplier Tubes (PMTs) exploit the internal electron multiplication process (cascaded secondary electron emissions in vacuum) and attain internal gain of about 10^6, hence in response to single-photons they produce electrical signals well above the noise of the readout electronics. PMTs can be exploited at some extent, but microelectronic solid-state detectors are strongly favoured not only for practical reasons (miniature size, easy of use, etc.), but also for attaining higher performance, in particular higher quantum efficiency (QE).

The Superconducting Single Photon Detector (SSPD) has low noise and low time-jitter (30 ps) when operated at extreme cryogenic temperatures (2.4 K) [5]. It is capable of high count rates (in the GHz range), but the active area is small (10 µm × 10 µm) and it requires bulky cryostats.

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Semiconductor Avalanche Photodiodes (APDs) have the typical advantages of solid state devices (small size, low bias voltage, low power consumption, ruggedness and reliability, etc.). However, APDs operated in linear mode (for which the output photocurrent is proportional to the input optical power) attain an internal gain that is not sufficient to detect single photons. Instead, single photons can be efficiently detected by means of avalanche diodes operating in Geiger-mode, known as Single-Photon Avalanche Diode (SPAD). Avalanche PhotoDiodes benefit from internal gain due to a process known as impact ionization that leads to the generation of multiple electron-hole pairs per input photon (the so-called avalanche gain). Applying a larger reverse voltage to the avalanche detector will result in a larger gain, until the breakdown voltage V_{BD} is reached. For bias voltages larger than V_{BD}, the electron-hole generation process becomes self-sustaining and results in a run-away process, which gives rise to an easily detectable macroscopic current. In this case, the detector is sensitive to a single photon input and is referred to as a Single Photon Avalanche Diode (SPAD) [6]. This mode of operation is often referred to as 'Geiger mode' because of its similarity to Geiger-Muller detectors.

2. AVALANCHE PHOTODIODES FOR SINGLE PHOTON COUNTING

The SPAD detector is a p-n junction, reverse-biased above the breakdown voltage, V_B, in order to exploit the fast and intense avalanche build-up triggered by the absorption of a single photon. Depending on the SPAD design, one or both carriers of the photogenerated electron-hole pair impact ionize and ignite a multiplication process. Since the bias voltage exceeds the breakdown voltage, a self-sustained current swiftly builds up in the milliampere range. The sub-nanosecond rise of the avalanche current marks with high precision the photon arrival-time. A suitable circuit senses the avalanche, quenches the detector by lowering the voltage below the breakdown level, and finally resets the SPAD above breakdown to the quiescent level, in order to make the detector ready to be ignited by another photon.

Different quenching techniques are available. Gated quenching allows the avalanche to persist until the bias is reduced below V_{BD} according to the gate duration. Passive quenching employs a resistor in series with the SPAD so that the avalanche current induces a voltage across the resistor and drops the SPAD bias near V_{BD}. Active quenching uses circuitry to rapidly detect the presence of an avalanche and actively force the SPAD bias below V_{BD}.

3. SPADS FOR NEAR-INFRARED

The design of $In_{0.53}Ga_{0.47}As$/InP SPADs for the Near-Infrared (NIR) spectral range (up to 1.65 μm) must cope with different issues. The narrow bandgap of the infrared sensitive materials inherently implies high carrier thermal generation rate. Hence, for reducing the dark count rate (DCR) to tolerable level, the devices must be cooled below room temperature. Moderate cooling is sufficient for $In_{0.53}Ga_{0.47}As$/InP devices, which can operate in the range from 150 K to 220 K.

Care must be taken to avoid using high electric field in $In_{0.53}Ga_{0.47}As$, because the tunnel-assisted generation of carriers strongly enhances the dark count rate. To this aim, the separate avalanche and graded multiplication structure (SAGM) [7] (see Fig. 1) can be valuably exploited. The photons with the wavelength of interest (e.g., 1550 nm) are absorbed in the narrow-bandgap $In_{0.53}Ga_{0.47}As$ layer ($E_g \sim 0.75$ eV at 295 K), lattice-matched to InP. The photo-generated hole is then drifted toward a wider bandgap InP region ($E_g \sim 1.35$ eV) in which avalanche multiplication occurs.

3.1 Design criteria

The design criteria for SPADs (in Geiger-mode) are different from those of APDs (in linear-mode). In fact, the positive feedback in the avalanche process is no more a drawback for SPADs, but it is exploited for attaining the Geiger-mode operation. The equal or comparable ionization coefficients of holes and electrons in semiconductor materials for infrared-sensitive detectors, which plague the performance of APDs [8], do not set any problem to SPADs. Furthermore, peripheral leakage, which increases the dark current in linear APDs, is not multiplied and, therefore, it does not contribute to the dark count rate of single photon avalanche diodes since it does not trigger any avalanche [6].

When designing InGaAs/InP SPADs, the main issue to cope with is the relatively high dark count rate (DCR), due to carriers created by processes other than photo-excitation. Both thermal excitation and field-assisted generation of free

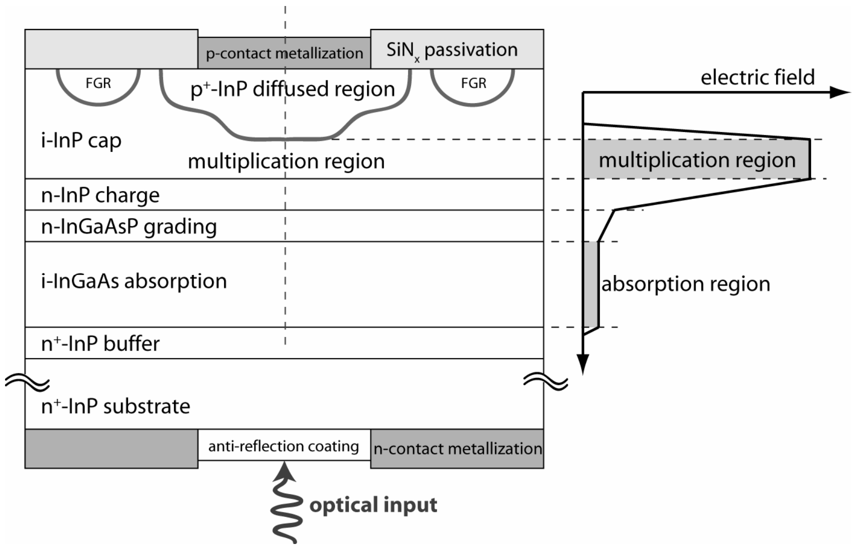

Fig. 1. Typical InGaAs/InP SPAD cross-section. The electric field profile highlights the absorption and multiplication regions.

carriers (i.e., tunneling processes) contribute to the dark count rate. When designing SPADs, their electric field profile should be optimized for operation at the target overvoltage V_{OV} (i.e. the excess bias between the applied reverse bias and the lower breakdown voltage). Therefore, a primary goal of the SPAD design is to maintain low electric field in the narrow bandgap *absorber* (to avoid dark current due to tunneling) while maintaining sufficiently high electric field in the *multiplication* region (so that impact ionization effects lead to significant avalanche multiplication).

An intermediate layer between absorption and multiplication regions could allow a more flexible tailoring of the internal electric field profile. Moreover the addition of a *grading* layer between the InGaAs and InP layers is important to reduce carrier (specifically hole) trapping effects that result from the valence band offset that arises in an abrupt InGaAs/InP heterojunction [9]. In particular, the total field control charge should be larger in a SPAD than in a linear mode APD to maintain low field amplitude in the absorption region while supporting higher field amplitude in the multiplication region thus allowing Geiger mode operation (see Fig. 1).

The lateral structure of our design employs a buried p-n junction to guarantee edge breakdown suppression, low perimeter leakage, and high reliability. The device active area geometry is determined by the patterning of a double Zn-diffusion, which creates a p^+-InP region within the i-InP cap layer (see Fig. 1). The two diffusions tailor the junction profile so that the junction is deeper in the central part of the active area than it is in the junction periphery, thus guaranteeing a uniform gain profile across the central part of the active region and a reduced gain in the peripheral region of the device.

Finally, thinner multiplication regions are desirable for reducing the noise of linear mode APDs and to obtain sufficiently high gain-bandwidth products. In contrast, SPAD performance benefits from much thicker multiplication regions (> 1 μm) due to the fact that their breakdown probability increases significantly faster with increasing overvoltage [10].

3.2 Device performance optimization

The assessment of SPAD performance goes through the evaluation of both photon detection efficiency (PDE) and dark count rate (DCR).

The photon detection efficiency depends on both the probability of absorbing a photon and on the probability that the photo-generated electron-hole pair succeed in triggering the self-sustaining avalanche process [11]. The former depends mainly on the thickness of the absorption InGaAs layer, while the latter rises first linearly with the overvoltage and tends then to saturate to unity at very high overvoltage [6][11] (Fig. 2). High overvoltage is desirable also for reducing the photon timing jitter. On the other hand, the primary DCR rises faster with the overvoltage (almost exponentially) due to the progressive enhancement of tunnel-assisted generation of carriers, as illustrated in Fig. 2.

The primary dark count rate of InGaAs/InP SPADs has different causes: temperature-assisted processes and field-assisted processes, which occur in more than one layer of the device structure with different intensities.

The temperature-assisted phenomenon is the spontaneous thermal generation of free carriers, which is dominated by the Shockley-Read-Hall (SRH) processes in the depleted regions, mainly due to local defects and therefore related to the crystal quality. SRH generation is intense in the $In_{0.53}Ga_{0.47}As$ absorber because of the small band-gap (0.752 eV) and can be reduced with high quality lattice.

Field-assisted mechanisms include direct band-to-band tunnelling and trap-assisted tunnelling. Both these generation processes become important when the electric field is high enough (i.e. in the InP multiplier) to give a finite probability of quantum tunnelling and depend exponentially on the electric field, mainly in devices with thin multiplication layers. The result is that increasing the overvoltage V_{OV}, the DCR increases exponentially (Fig. 2). In [13][14], the trap-assisted tunnelling in the multiplication layer has been identified as the dominant field-assisted mechanism of InGaAsP/InP avalanche diodes, designed for applications at 1064-nm wavelength. Therefore, in order to achieve low primary DCR for such devices, the defect density in the InP multiplication layer has to be kept as low as possible in order to keep trap-assisted tunnelling at low levels.

Tunnelling mechanisms are important in the InP multiplication layer where the electric field exceeds $4 \cdot 10^5$ V/cm, while they are unlikely in the absorber. Anyhow, effects due to high electric field may make the transition between a local level and a band easier, thereby significantly enhancing the thermal generation both in InGaAs and in InP, similarly to what has been recently ascertained for Silicon SPADs [15].

Nowadays, the most demanding applications require very low dark count rates in order to maximize the signal-to-noise ratio. The detection efficiency of commercially available devices is good, being higher than 20% at 1550 nm (see Fig. 2). On the other hand, the dark count rate has to be improved.

In [16], the dependence of the performance of InGaAs/InP SPADs on the thickness of the multiplication layer at low temperatures has been numerically calculated. By comparing the effects of field-assisted dark carriers with temperature-assisted dark carriers, as the width is varied while keeping constant the triggering probability, it resulted that the tunnelling current decreases as the thickness of the multiplication region increases due to the lower electric field. Moreover, an optimal multiplier thickness that achieves the maximum photon detection efficiency has been identified, resulting from the counteracting effects of the decrease of the tunnelling and the increase of carrier generation rate when increasing the layer thickness.

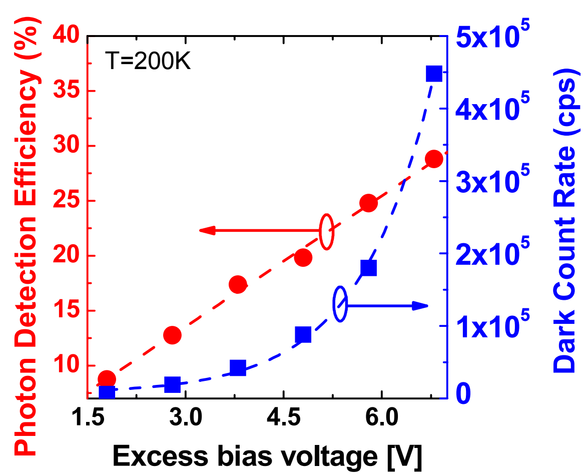

Fig. 2 Dependence on the overvoltage of the photon detection efficiency at 1550 nm and of the primary dark count rate of an $In_{0.53}Ga_{0.47}As$/InP SPAD (previous generation PLI device with 40-µm diameter [12]).

Following such calculation, a new device with thicker multiplication layer has been designed and manufactured at Princeton Lightwave Inc. (PLI). The resulting device showed lower primary dark count rate due both to thicker InP layer and to the improvement of InGaAs lattice quality, which led to lower generation-recombination.

4. EXPERIMENTAL CHARACTERIZATION

4.1 Dark count rate and photon detection efficiency

During our experimental characterization, we operated the photodetector in passive gated mode. When the device is kept off (T_{OFF} time interval), the SPAD bias is 0.5 V below the breakdown voltage, whilst when the SPAD is turned on (T_{ON} time interval) the SPAD bias is V_{OV} (i.e. the overvoltage) above the breakdown level.

In order to characterize only the primary dark count rate, avoiding the afterpulsing effect (which plagues SPAD detectors), long off-times (either T_{OFF} = 1 ms or T_{OFF} = 200 µs) have been employed. In order to compensate for the duty cycle, all the data have been corrected according to the following equation:

$$DCR = -\frac{1}{T_{ON}} \cdot \ln\left(1 - \frac{N_{counter}}{f_{GATE}}\right)$$

where $f_{GATE} = 1/(T_{ON}+T_{OFF})$ is the gate frequency and $N_{counter}$ is the avalanche rate in gated mode as measured by a photon counter.

Fig. 3 compares the primary DCR of a previous ("old") generation of Princeton Lightwave InGaAs/InP SPAD with a new generation device, as a function of temperature. The old device has an active area diameter of 40 µm, whilst the new one has a diameter of 25 µm. For the old device, there is an exponential dependence of the DCR with temperature with a single slope even at very low temperatures. For the new SPAD, the DCR strongly depends on temperature in the range from 300K to 225K, whilst its dependence is fainter at low temperatures (200K – 150K). Therefore, at high temperatures the main primary DCR contribution is thermal generation, whilst at low temperatures the main contribution is tunnelling (either trapped assisted or band-to-band). The new device benefits from higher quality InGaAs absorption layer, which reduces the thermal generation, and wider InP multiplication region, which reduces tunnelling. Anyhow, at very low temperatures, the tunnelling generation is still a limit.

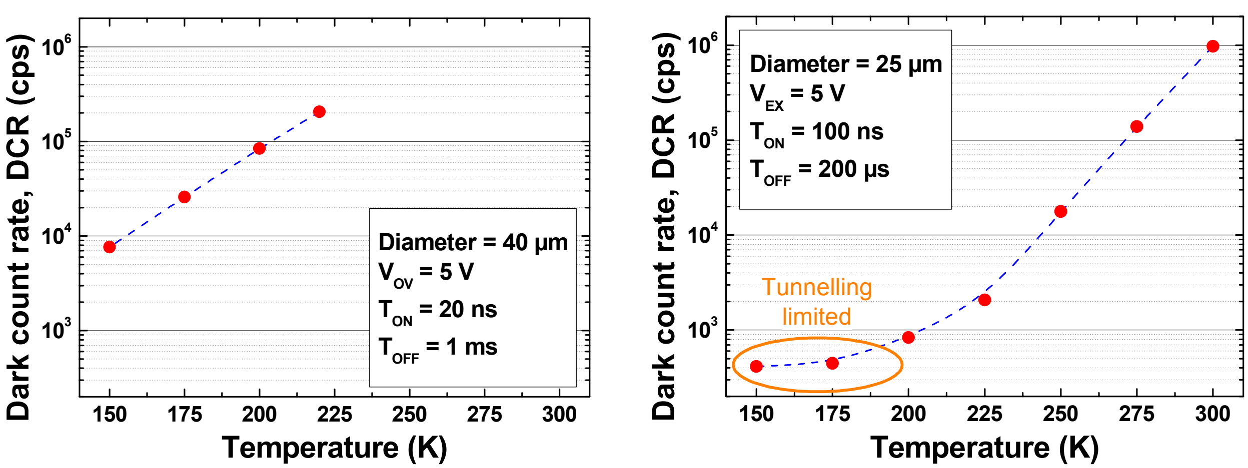

Fig. 3 Dependence on temperature of the primary dark count rate of an old (left) and a new (right) generation of $In_{0.53}Ga_{0.47}As$/InP SPAD.

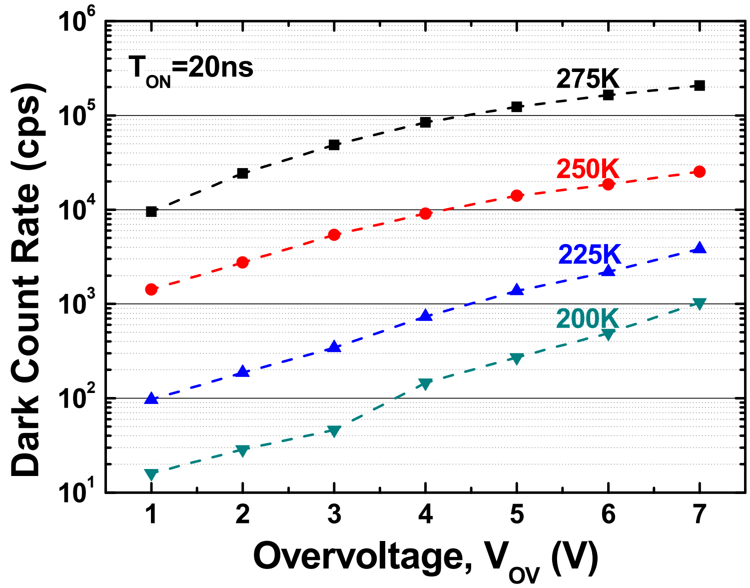

Fig. 4 Dependence on overvoltage of the primary dark count rate of a new $In_{0.53}Ga_{0.47}As/InP$ SPAD (25-µm diameter).

In order to fairly compare the quality of the two technologies, we computed the DCR per unit active area (cps/µm^2) at 200 K:

Old generation device: $DCR_{\text{unit area,old}} = 120$ cps/µm^2

New generation device: $DCR_{\text{unit area,new}} = 1.6$ cps/µm^2

By computing the ratio, we obtain an improvement of a factor of 120/1.6 = 75 from the previous to the last PLI InGaAs/InP SPAD generations.

We investigated also the dependence of the DCR on the overvoltage at different temperatures (see Fig. 4). The DCR has an almost exponential rise with the overvoltage at high temperatures, which confirms that the thermal generation rate is strongly enhanced by higher electric field.

Our preliminary measurements show a strong improvement of the primary DCR with respect to previous InGaAs/InP SPAD generation. In order to obtain better statistics of such improvement and to quantify the parameter spreading over the production wafer, further experimental data on more samples (possibly with different active areas) are needed.

4.2 Afterpulsing

The afterpulsing effect introduces a secondary source of dark counts, with carrier generation rate proportional to the trap level population. Nowadays, this effect limits the application of $In_{0.53}Ga_{0.47}As/InP$ SPADs and it rules out free running operation of the detector.

During every avalanche current flow, some carriers get trapped in deep levels inside the multiplication region. Unluckily, these levels have fairly high concentrations and fairly long lifetimes in InP, since the time constants that rule the dynamics of the population range from ten microseconds up to few tens of microseconds at 220K and remarkably increase as the temperature is further decreased. It is clear that a trap level in the InGaAs absorber is totally ineffective, because there only the concentration of avalanche electrons is high and a released electron cannot trigger the avalanche (in fact, it travels away from the high field region). Only the trap levels in the multiplier InP region do matter for afterpulsing.

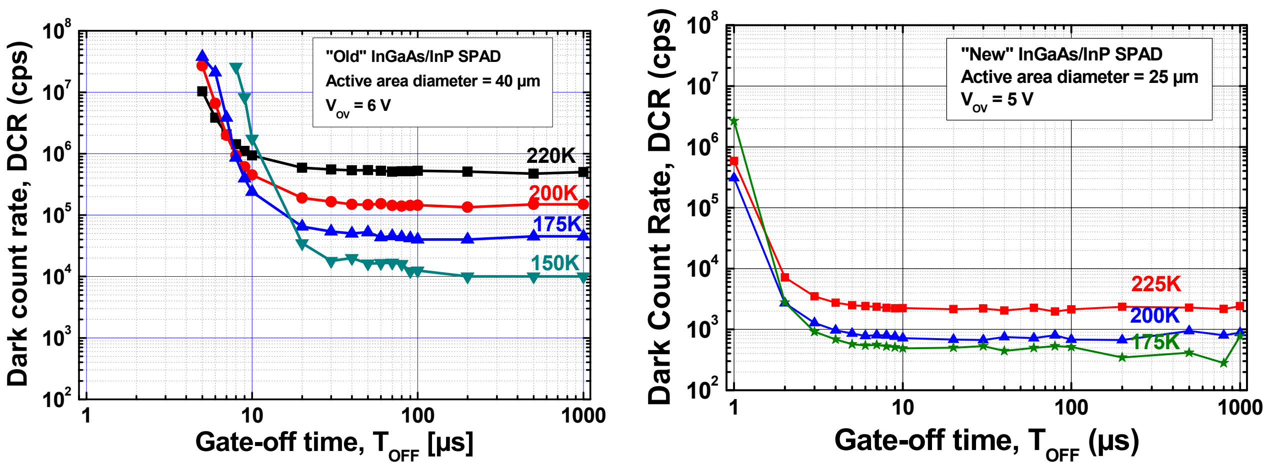

Fig. 5 Dark count rate of old (left) and new (right) generation of InGaAs/InP SPAD devices at various temperatures in gated operation (T_{ON} = 20 ns) as a function of the idle interval T_{OFF}.

Fig. 5 compares the DCR dependence on the off time-intervals (T_{OFF}) for both the previous and the last SPAD generations. Besides the DCR, also afterpulsing has been reduced, since the DCR increases at shorter T_{OFF}. However, it is unusual that afterpulsing is quite independent from the off time in the whole wide range of temperatures (150 K – 300 K). Further investigations are needed to better explain such behavior.

Since the DCR of new PLI SPADs is quite low, we experimentally characterized it also at high temperature, even up to room temperature (300 K). Fig. 6 shows that moderate cooling (few degrees below 0 °C, achievable with one-stage thermoelectric cooler) is enough for attaining a DCR comparable with the old device cooled at 200 K (achievable with three-stage thermoelectric cooler).

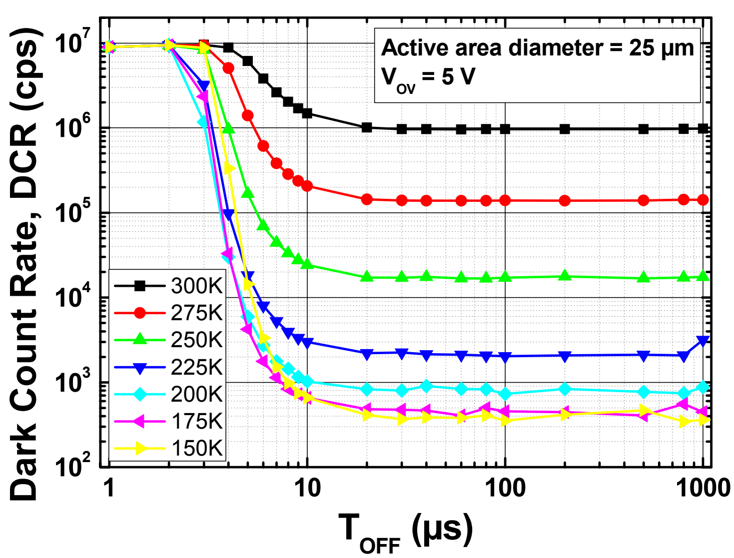

Fig. 6 Dark count rate of a new InGaAs/InP SPAD device at various temperatures in gated operation (T_{ON} = 100 ns) as a function of the idle interval T_{OFF}.

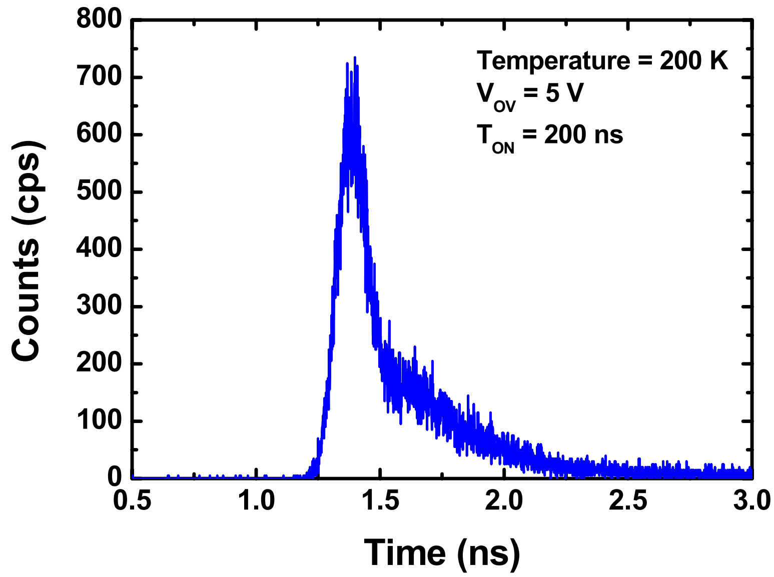

Fig. 7 Photon timing jitter of a new generation InGaAs/InP SPAD operating at 200 K, 5-V overvoltage and with differential sensing front-end for optimizing signal pick-up.

4.3 Timing jitter

Suitable signal pick-up circuits can be employed for extracting at best the photon-timing information [18] and, in order to attain high resolution in photon timing, the electronic circuit should extract the time information from the very first part of the avalanche pulse [19].

We employed an R_P-C_P pick-up network for sensing the fast avalanche current signal from the SPAD anode, while connecting the gate pulse generator directly to the cathode.

We illuminated the SPAD with a 1550-nm pulsed laser with pulse width of about 20 ps (Full Width at Half Maximum, FWHM). The gate duration is T_{ON} = 200 ns, and the gate frequency is f_{GATE} = 10 kHz.

When the device is biased at 5-V overvoltage, the time response to the laser pulse is as shown in Fig. 7. The time jitter is 100 ps (FWHM). Such value is worst than that of the previous PLI run (about 40 ps). Such behaviour may be due to either process non uniformity and more measurements on different devices are needed.

5. CONCLUSIONS

Preliminary measurements on a new generation of $In_{0.53}Ga_{0.47}As/InP$ SPADs have been presented and device performances have been compared with those of the previous run. Such new devices proved to be better in terms of dark count rate and signal-to-noise ratio. The detector dark counts have been strongly reduced, while keeping the photon detection efficiency constant. When cooled at 225 K, a temperature achievable with simple single-stage thermo-electric coolers, the dark count rate of a 25-µm detector is lower than 1 kcps, even when the detection efficiency is higher than 20 %. The afterpulsing has slightly improved, but it is still the main issue and rules out free-running. The measurements on timing jitter show that the timing jitter is less than 100 ps (FWHM).

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