Performance evaluation of InGaAs/InP SPAD for high clock rate QKD

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Abstract

Newly developed InGaAs/InP SPADs have good detection efficiency and fairly low dark-count rate at moderately low temperature. By means of experimental studies on primary dark counts, we investigate how thermal generation and trap-assisted tunneling affect the device performance at various temperatures. Moreover, the effectiveness of trapping levels as a function of their location and of the electric field distribution is studied by computer simulation in order to gain a better understanding of afterpulsing. Picosecond photon timing information is extracted even with ultrafast gate transitions thanks to custom fast electronics.

Introduction

The main challenge for the widespread diffusion of secure fiber networks based on Quantum key distribution (QKD) is to achieve high clock rates. Currently, a technological bottleneck is given by the maximum count rate of single-photon detectors.

Superconducting Single-Photon Detectors [1] have low noise due to cryogenic temperatures (2.4 K), low time jitter and are capable of high repetition rates, but the quantum efficiency is limited, the active area is small and, above all, they require bulky cryostats. Such characteristics make them unpractical for building wide and reliable secure network.

InGaAs/InP Single-Photon Avalanche Diodes (SPAD) have an internal structure similar to linear-mode APDs, but recently devices have been specifically designed for Geiger-mode operation. The positive feedback in the avalanche process is exploited in order to build-up an avalanche pulse even when a single photon is absorbed. They proved to be a good choice in terms of performance, cost and reliability.

InGaAs/InP SPAD dark counts

The photon is absorbed in the $In_{0.53}Ga_{0.47}As$ layer and it generates an electron-hole pair. The hole is then drifted towards the multiplication InP layer where it triggers an avalanche thanks to the high electric field. Since the InGaAs bandgap is small (0.75 eV), the electric field in the absorption layer has to be kept low in order to avoid tunneling that would increase the dark count rate. Therefore, a grading InGaAsP charge layer between the InGaAs and the InP layers is used to tailor the electric field profile. High electric fields in the InGaAsP and InGaAs layers would increase the dark count rate because of field-assisted mechanisms such as direct band-to-band tunneling and trap-assisted tunneling in the InGaAs epitaxial layer. Therefore, the electric field in the absorption layer has to be kept quite low.

We experimentally measured the Dark Count Rate (DCR) of InGaAs/InP SPAD devices produced by Princeton Lightwave (PLI) [2] at various temperatures and different excess bias voltages. The detectors are operated in gated mode, with the bias voltage pulsed above breakdown for a short gate-on interval, T_{ON}, whereas during the idle gate-off interval, T_{OFF}, the bias is below breakdown.

Our results confirm that DCR has an exponential dependence on both temperature and overvoltage, meaning that there are both thermal and field-assisted mechanisms. Taking into account the band-gap of the various layers, it is possible to conclude that the main causes of dark counts in InGaAs are the Shockley-Read-Hall generation and the field-assisted thermal generation, whereas in InP trap-assisted tunneling is dominant. Therefore, the primary DCR can be reduced by improving the crystalline quality of both InGaAs and InP. From Arrhenius plots of DCR measured at different temperatures and at different overvoltage values, we extracted an activation energy E_a=0.14 eV, which points out moderately deep energy defects in the bandgap. Further investigations are needed in order to precisely identify the main defect types.

Afterpulsing

The afterpulsing effect introduces a secondary source of dark counts, with carrier generation rate proportional to the trap level population. Unluckily, these levels have fairly high concentrations and fairly

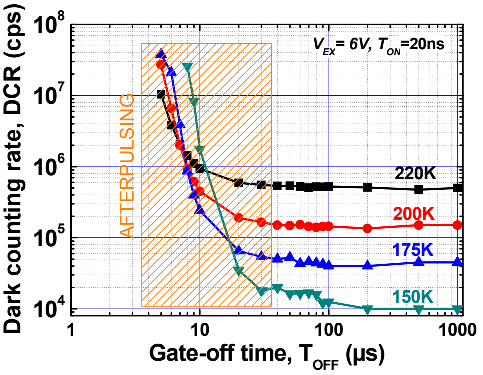

Figure 1: Dependence of DCR of PLI InGaAs/InP SPADs on gate-off time at various temperatures.

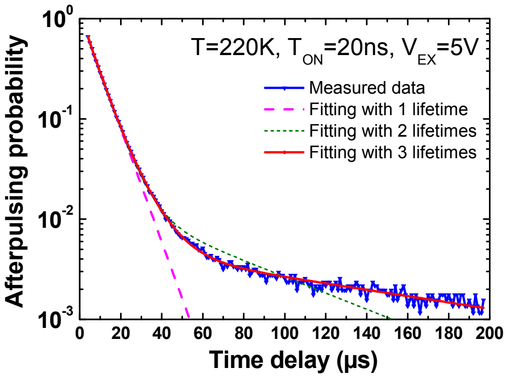

Figure 2: Release transient of trapped carriers, obtained with double-pulse gated measurement.

long lifetimes in InGaAs/InP SPADs. As a result, afterpulsing is crucial for high count rate applications, such as QKD.

As shown in Figure 1, at short T_{OFF}, the DCR rises by orders of magnitude, dominated by afterpulsing. Lowering the temperature decreases the primary DCR, but increases the minimal T_{OFF} required to avoid afterpulsing.

We characterized traps by means of the double-pulse method [3] and we fitted the resulting curve with a sum of exponential decays (Figure 2). Three lifetimes are required to fit the carrier release transient, denoting that at least three different trap species in the InP multiplier layer contribute to afterpulsing.

The number of filled traps is proportional to the total avalanche charge, which can be limited by proper selecting the operating conditions, such as lower overvoltage (but detection efficiency is reduced), higher temperature (but primary DCR is increased), higher electric field during off time, and fast quenching circuit (with quenching time of few ns). However, only a further progress of the device technology will allow to overcome this drawback and employ InGaAs SPADs in free running. A deep level can produce afterpulsing if it captures an avalanche carrier (with a probability that is proportional to the concentration of carriers during the avalanche) and the released carrier succeeds in triggering a new avalanche (avalanche triggering probability). Therefore, the product of the carrier concentration and of the triggering probability (Figure 3) can be used as a figure of merit to assess in which zone of the device a given trap level is more effective in producing afterpulses. It is worth noting that hole and electron traps are almost equally effective in InP and that the InGaAs region and the marginal layers do not contribute to afterpulsing. For reducing afterpulsing, the highest attention should be given to the crystal quality in the central part of the multiplier region.

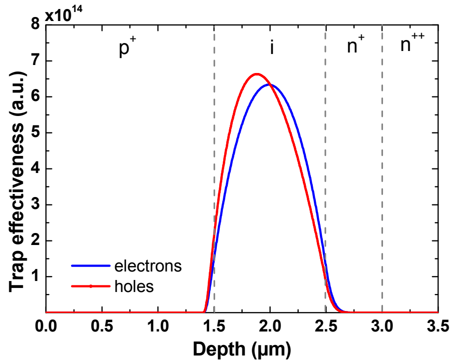

Figure 3: Carrier trap effectiveness versus depth position in the InP multiplier region.

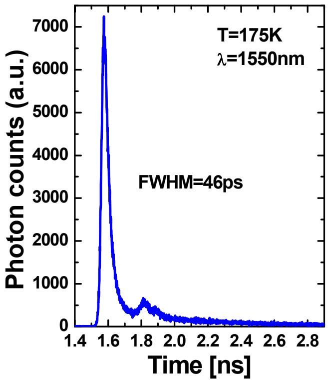

Figure 4: Photon timing jitter of an InGaAs/InP SPAD.

Time jitter

Special signal pick-up circuits must be employed for extracting at best the photon-timing information. The electronic circuit should extract the time information from the very first part of the avalanche build-up. A capacitive pick-up network was designed for sensing the fast avalanche current signal from the SPAD anode. The gate pulse is applied to the cathode and a special differential sensing circuit is employed for neutralizing spurious feed-through pulses at comparator input. A time resolution of 46 ps FWHM was thus obtained (Figure 4).

Conclusions

We present the results of experimental studies on InGaAs/InP SPADs. The primary DCR is quite low, even at temperature achievable with thermoelectric coolers. Thanks to a differential read-out circuit, the time jitter is less than 50 ps. Though a complete solution of the afterpulsing is demanded to progress in device technology, with proper operating conditions significant reduction is obtained.

References

1. G. N. Gol'tsman et al, IEEE Trans. On Applied Superconductivity, 11, pp. 574-577, 2001.
2. M. A. Itzler et al, J. Mod. Opt., vol. 54, no. 2–3, pp. 283–304, 2007.
3. S. Cova et al, Electron Device Letters, IEEE, vol. 12, no. 12, pp. 685-687, 1991.