Thermoelectrically cooled operation of InGaAs/InP photon counters at the eyesafe wavelength

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ABSTRACT

We have investigated the performance of separate absorption multiplication InGaAs/ InP avalanche photodiodes as single photon detectors for the 1.55 µm wavelength. We have optimized the active quenching and gating circuit, tailored for operation of these diodes at the temperatures in the range from the room to the –60° Celsius achievable by means of a thermoelectrical cooling. The careful tuning of diodes operating conditions resulted in a significant reduction of the after-pulsing effects, thus permitting to operate the detectors with the repetition rates reaching 1 MHz, while maintaining the dark count rates of the order of 100 kHz. The noise equivalent power of 7×10^{-16} W/Hz$^{1/2}$ and the timing resolution of 3.2 nanoseconds have been obtained at 1.55 µm wavelength.

Keywords: infrared single photon detector, InGaAs avalanche photodiode, active quenching

1. INTRODUCTION

Operation of commercially available InGaAs/InP avalanche photodiodes as photon counters at high temperatures at the 1.55 µm wavelength is of special attention for numerous applications including time resolved spectroscopy, laser induced fluorescence, optical time domain reflectometry, quantum cryptography, eye safe laser ranging and imaging and others. The 1.5 µm wavelength region is of special interest for two reasons: 1.55 µm corresponds to the third telecom window for optical communication and quantum cryptography and 1.54 µm is the so-called eye safe laser ranging wavelength[5]. At present, the most promising technique to detect single photons by use of a solid state detector is an avalanche photodiode (APD) operated in the Geiger mode. In this operating mode the diode is pulse biased above its breakdown voltage; no current is flowing until an avalanche is triggered by an incoming photon or a thermally generated carrier. The current pulse rise time marks the photon's arrival time. An external electrical circuit, either passive or active[6], is used to quench the avalanche and to re-apply the bias to the diode.

Our previous research and development in the field of single photon avalanche diodes resulted in a large aperture silicon APD based detector package with and active quenching circuit well adopted for applications listed above[4]. Recent developments resulted in an custom designed APD having a diameter of 0.2 millimeters in diameter, a timing resolution of 44 picoseconds FWHM and a dark count rate below 10 kHz. The APD chip is cooled by a three stage thermoelectrical cooler and enclosed in a miniature evacuated package. The quantum efficiency corresponds to the silicon, it drops for the wavelength longer than 1.1 µm, for 1.5 µm wavelength region the silicon APD is unusable. Several attempts have been made to fabricate the APDs suitable for photon counting in the near infrared on the basis of the GeSi mono-crystal in our lab, however, the development is still continuing.

One of the candidates for detection in the 1.5 µm region is the germanium APD. We have developed the large aperture germanium detector package[3] for picosecond photon counting in the wavelength range 0.5 to 1.6 µm. This package has been used as an echo signal detector in the satellite laser ranging system operating at so-called eye safe wavelength 1.54 µm in the Communication Research Labs., Tokyo, Japan[5]. Although this detector package is performing well for satellite laser ranging purposes, its use in other application is limited: the cryogenic environment is needed and the dark count is of the order of 1 MHz.

The separate absorption multiplication (SAM) avalanche photodiodes InGaAs/ InP are another candidates to sense single photons. The use of the InGaAs/InP avalanche photodiodes for photon counting in the near infrared has been reported by several authors already[1,2,5]. These diodes have been found to be the best known candidates on photon counting sensors from the point of view of quantum efficiency at 1.55 µm. They have been tested at broad range of temperatures ranging from the room down to the 77 K, the detection efficiency of single photon of several percents and the time response from microseconds down to 200 picoseconds has been reported[1]. All the reported results have been obtained using the commercially available separate absorption multiplication (SAM) avalanche photodiodes InGaAs/ InP chips, which have been designed, optimized and manufactured for another application different from the photon counting in the Geiger mode.

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In all the publications conclusions the authors stated, that better results are expected, once such diode structures will be designed and tailored specifically for the photon counting, like the silicon and germanium detection chips. However, the operational structures of SAM avalanche photodiodes InGaAs/ InP specifically tailored for photon counting have not been manufactured, yet. The InGaAs manufacturing technology complexity and cost is, probably, limiting the development process of such a structure. Additionally, most of the reported experiments with these diodes have been carried out in a cryogenic environment at temperatures 77 K to 180 K in order to achieve acceptable dark count rate and detection sensitivity. Although the compact closed cycle cryo-coolers are currently available, their size, consumption, lifetime, complexity and cost are not suitable for most of applications, the telecommunication as the principal one.

Considering the achievements listed above on one hand and the foreseen applications on the other hand, we have focussed our attention to optimization of the SAM InGaAs/ InP diodes operating conditions in an attempt to construct a compact, all solid state photon counter operating in the 1.55 μm region with following parameters: based on commercial chips, high photon detection probability at 1.55 μm, high timing resolution, high operational repetition rate, simple thermoelectrical cooling, compact and rugged design, reliable operation

2. PHOTON COUNTING DETECTOR PACKAGE

The solid state photon counter is based on an avalanche photodiode operated in the Geiger mode. In this operating mode the diode is pulse biased above its breakdown voltage short time before the expected arrival of photon of interest. No current is flowing until an avalanche is triggered by an incoming photon or a thermally generated carrier. The current pulse rise time marks the photon's arrival time. An external electrical circuit, either passive or active, is used to quench the avalanche and to control the diode bias control and gating.

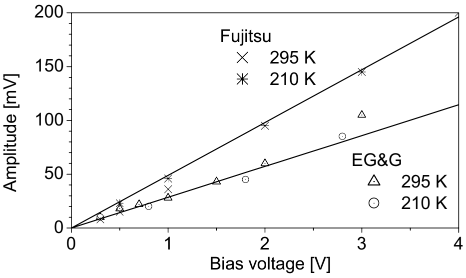

Figure 1: Output pulse amplitude EG&G and Fujitsu diodes versus voltage above break, diodes have been operated in a passive quenching mode at 210 K and 295 K, pulses recorded on a digitizing scope with the analog bandwidth 400 MHz.

Two types of commercially available diodes have been used Fujitsu FPD5W1KS diodes, having 30 μm diameter active area and the EG&G diodes C30644E having the active area diameter 50 micrometers. The amplitude of the diode output pulse as a function of the voltage above break is plotted on Figure 1, the dependence of a break voltage on the temperature is plotted on Figure 2. These values have been measured operating the diodes in an Geiger scheme, in series with the 1 MegaOhm resistor blocked by capacitor 20 picoFarads, the output pulses have been recorded on a digitizing scope with 400 MHz bandwidth.

The main parameters of the photon counting detector are the detection efficiency, timing resolution, dark count rate and the maximum achievable detection repetition rate. The main parameters of the photon counting detector depend, aside of the construction of the diode structure itself, on the operating conditions of the APD:
operating temperature – the number of thermally generated carriers inside the semiconductors is decreasing with temperature. Thus, decreasing the temperature will result in a decrease of a dark count rate of the detector. The decrease of a dark count rate is one of the main reasons for the detectors cooling. Additionally, the temperature influences the break voltage of the diode. Due to the complex structure of the separate absorption multiplication avalanche photodiode InGaAs/InP the temperature also significantly influences the detection efficiency and timing resolution at 1.55 μm wavelength[1].

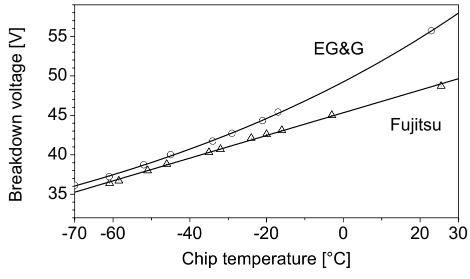

Figure 2: Break voltage of the EG&G and Fujitsu diodes versus temperature.

diode bias – the voltage, for which the APD is biased above its break voltage, is influencing all the main detector parameters: detection sensitivity, timing resolution and dark count rate. In general, increasing the bias above the break, the photon counting detection sensitivity will increase and will be saturated at certain voltage. Increasing the bias the timing resolution of the detector will improve and will be saturated at some level. Increasing the bias above break, the dark count rate of the detector will increase.
operation repetition rate – the rate, with which the detector, operated in the gated mode, is repeatedly activated. The detection rate is limited by the after-pulsing effects[1] – the lifetime of carriers persisting in the detection structure after the previous breakdown event. In general, the afterpulsing effects are less significant at higher temperatures. However, simultaneously, the afterpulsing probability is increasing with dark count rate, which increases with temperature.

quenching and gating circuit – its construction determines the process of diode operation as the photon counter. The circuit impedance influences the avalanche current buildup, the circuit internal delays determine the time, for which the avalanche is building up before being quenched. The total avalanche charge, the number of generated carriers, is influencing the afterpulsing.

On the basis of the previous description one can conclude, that the operating conditions settings and a design and construction of the quenching and gating circuit represents a complex task. The resulting solution is always a compromise tailored to the specified application. The photon counter time resolution, detection efficiency, dark count rate and maximum detection rate are subjected to a delicate trade-off.

3. ACTIVE QUENCHING AND GATING CIRCUIT

The block scheme of an active quenching and gating circuit is on Figure 3. The rise of the current flowing across the diode is sensed by the fast comparator, its output controls the APD biasing and generation of the uniform output signal. The detector is enabled by the external gate signal. The active quenching circuit has been developed by S.Cova[6] for Si APDs operated as photon counters and modified for various applications later on[4]. The similar scheme of the active quenching and gating circuit is also suitable for operation of the photon counter based on the germanium avalanche photodiode and operated in a cryogenic environment[3]. Recently, such a circuit has been used in our laboratory to active quench and to gate the photodiode structures fabricated on the basis of GaAs, GaP and GaAsP, as well. However, standard active quenching and gating schemes are far from optimum to operate the SAM InGaAs/InP photodiodes as photon counters. There are two main reasons: the differential serial resistance of the InGaAs/ InP diode above its break is several times higher in comparison to the silicon and germanium diodes. Thus, the avalanche sensing comparator must be capable to respond to pulses. Additionally, due to the strong influence of the afterpulsing, it is desirable, to keep the total charge flowing across the structure after a break minimal, it means, to lower the diode bias below the break as soon as possible. These two requirements are in direct contradiction – more sensitive (higher gain) comparators have higher propagation delays and vice versa.

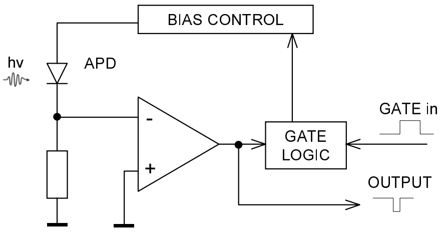

Figure 3: Block scheme of an active quenching and gating circuit.

We have developed a new active quenching and gating circuit designed specifically for the SAM InGaAs/ InP diode structures. The circuit has been optimized from the point of view of avalanche current sensitivity and a total charge flowing through the diode after the break. Additionally, the circuit allows to adjust the slew at which the diode is biased above the break to minimize the transient effects on the beginning of the gate on switching.

4. EXPERIMENTAL SETUP

The active quenching and gating circuit has been used to operate the SAM InGaAs/ InP diodes as photon counters. Two types of commercially available diodes have been used Fujitsu FPD5W1KS diodes, having 30 µm diameter active area and the EG&G diodes C30644E. Both fiber pigtailed (2 samples) and unpacked (2 samples) chips of the Fujitsu have been tested together with the unpacked EG&G diodes (2 samples). The measured results were quite close for the same diode type. The chips have been cooled and temperature stabilized in the temperature range –70° to +30° Centigrade. The arrangement of the test setup is plotted on Figure 4. The standard scheme of the time correlated photon counting experiment has been used. The laser diode operating at 1.55 µm has been driven by the current pulses from the driver generating optical pulses 100 or 400 picoseconds long with the optical peak power of 10 milliWatts. The 400 picoseconds pulses have been used for sensitivity tests, the 100 picosecond pulses have been used for ultimate timing resolution tests. The signal has been attenuated using the neutral density filter ND. The APD diode under test has been placed in a cooling chamber, the water condensation has been avoided by dry atmosphere surrounding the diode. The active quenching and gating

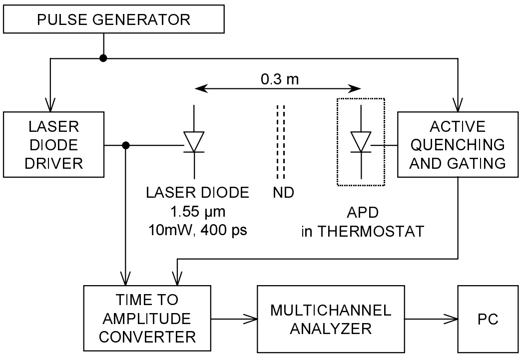

Figure 4: Experimental setup for InGaAs/InP diodes tests.

circuit generated the NIM timing pulses. The time to amplitude converter (TAC) manufactured by EG&G provided the ultimate timing resolution of 20 picoseconds. The data from the TAC have been processed in the multichannel analyzer card in a personal computer. The gate signal has been generated and the repetition rate of the experiment has been controlled by the pulse generator.

5. DETECTOR PERFORMANCE RESULTS AND DISCUSSION

The example of the output data is on Figure 5. It represents a time correlated photon counting histogram. The EG&G SAM InGaAs/InP diode was operated 0.5 V above break, the diode was kept at the temperature –48° Centigrade, the timing resolution was 160 picoseconds per channel. The experiment has been completed at the repetition rate of 10 kHz. Considering the photon counting statistics, the dark count rate has been computed (260 kHz in this case), the timing resolution of 3.2 nanoseconds has been obtained. As the laser diode output pulse length and the timing electronics resolution are much shorter, this value corresponds to the timing resolution of the photon counting detector itself.

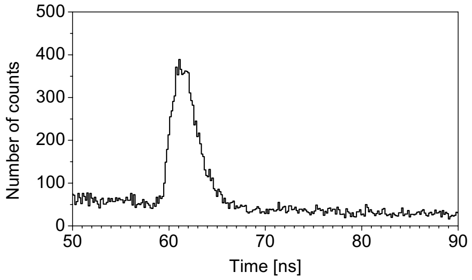

Figure 5: Example of the experimental data, the EG&G diode 0.5 V above break, –48° Centigrade, horizontal scale 160 picoseconds per channel, repetition rate of 10 kHz. The timing resolution FWHM = 3.2 nanoseconds, considering the photon counting statistics, the dark count rate of 260 kHz has been computed.

The photon counting sensitivity has been estimated from the corrected useful signal detection rate. The photon detection probability in absolute figures has been computed from the experiment energy balance: the laser output power was 10 mW, the laser pulse length 400 picoseconds, the total energy generated at 1.55 µm is 4×10^{-12} Joules per pulse. Taking into account the experiment geometry: distance of the photon counter from the laser diode (300 mm), active are of the detector, the radiation pattern of the single mode laser diode and the neutral density filter involved (transmission 50 %), the average number of photons per laser shot hitting the detector active area may be computed. The resulting average photon flux density was one photon and 0.3 photon per laser shot for the detector active area diameter 50 and 30 micrometers, respectively. In the optimized configuration (see later): -48° Centigrade, 0.5 V above the break, using the EG&G diode, the photon detection probability reached 12 %. Considering the estimated photon flux on the diode aperture, the quantum efficiency of 12 % has been calculated for EG&G diode. For

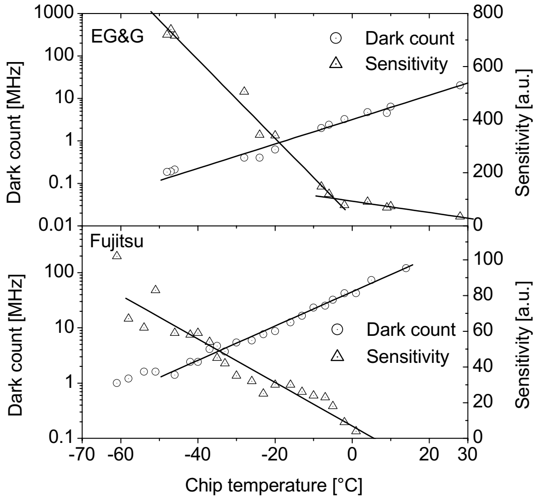

Figure 6: Dark count and relative sensitivity as a function of temperature, 0.5 V above break, EG&G diode (top) and Fujitsu diode (bottom).

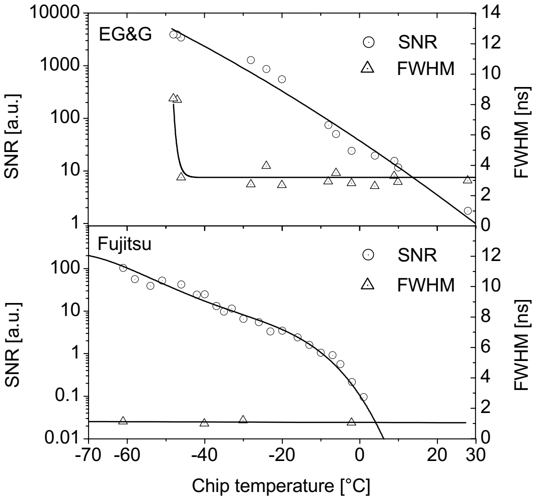

Figure 7: Signal to noise ratio and timing resolution as a function of temperature, 0.5 V above the break EG&G diode (top) and Fujitsu diode (bottom).

Fujitsu diodes operated 0.5 Volts above break at –61° Centigrade the detection probability was 3.3 %, considering the estimated photon flux on the diode aperture 0.3 photon per laser fire, the quantum efficiency of 11 % has been calculated for Fujitsu diode.

The dependence of the dark count rate and the relative sensitivity on operating temperature is plotted on Figure 6. The diodes have been operated 0.5 Volts above their break voltage. The dark count rate of both the diodes is monotonically decreasing with the factor of 6 times each 10 K. The relative sensitivity of the Fujitsu diode is monotonically increasing with the decrease of diode temperature. Above the zero degrees Centigrade, the sensitivity of the Fujitsu diode was too low to be measured in a given setup. The sensitivity of the EG&G diode is exhibiting more complex temperature dependence. It is increasing with decreasing temperature, the slope is significantly increased bellow 0° Centigrade. It is worth to mention here, that the dark count rate of the EG&G diode is more than one order lower in comparison to the Fujitsu diode, the dark count rate of the EG&G at –48° Centigrade is as low as 260 kHz.

The dependence of the photon counting detector timing resolution and signal to noise ratio on temperature is plotted on Figure 7. The EG&G diode SNR ratio is exhibiting certain break of the characteristics at 0° Centigrade. The timing resolution is practically constant within the entire temperature range with the steep increase for temperatures bellow -48° Centigrade. At these temperatures, an additional mechanism is taking place in the InGaAs/InP structure causing the split of the detection delay within two values. Obviously, constructing the photon counting detector, the lowest possible dark count with the acceptable timing resolution is desired. That is why, the temperature close to –48° Centigrade is of a special interest. In contrast the Fujitsu diode is not exhibiting any of these effects, the time resolution remains more or less constant over the entire temperature range.

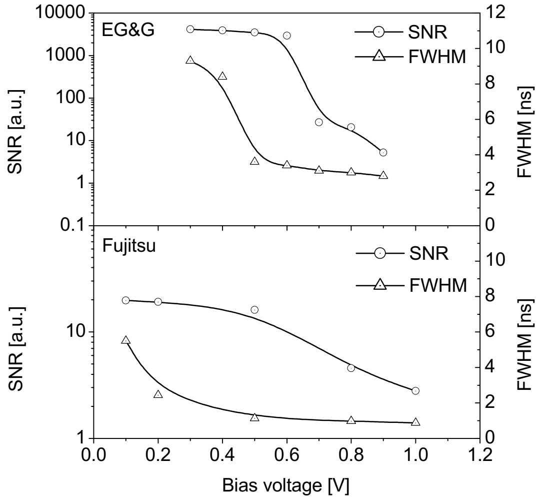

Figure 8: Signal to noise ratio and timing resolution as a function of voltage above break, EG&G diode at –48° C (up) and Fujitsu diode at –61° C (bottom).

On Figure 8 there is a plot of the signal to noise ratio and the timing resolution as a function of the bias above the break at a fixed temperature. For EG&G diode, the SNR remains relatively high for biases 0.1 to 0.6 Volts above break and drops significantly for biases 0.7 Volts and more above the break. The timing resolution is significantly increased for biases higher than 0.4 Volts above the break. It means, that there exists a clearly defined optimum biasing of the diode for the given temperature. For -48° Centigrade the optimum bias is 0.55 Volts above the break with the tolerance 0.1 Volt only. Considering the break voltage temperature dependence of the diode about 0.16 Volt per degree Centigrade one can conclude, that the diode chip temperature has to be stabilized with the accuracy at least 0.5° Centigrade.

The Fujitsu diode temporal resolution and SNR is on Fig. 8 below. No significant optimum may be observed. It is worth to mention that the timing resolution of the Fujitsu diode will be greatly improved for higher biases above the break. However, the unrealistic dark count rates dark count rates appear at these temperatures. In general, the Fujitsu diodes exhibit higher timing resolution and much higher dark count rate in comparison to the EG&G diodes in the observed temperature range.

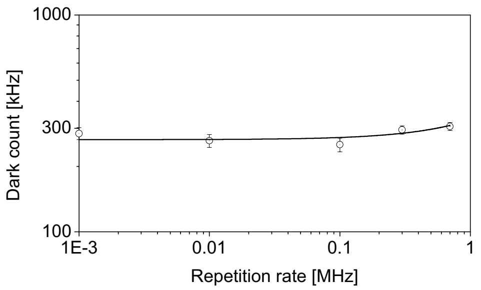

Figure 9: The dark count rate versus gate repetition rate for the optimum detector configuration, EG&G diode biased 0.5 Volts above break, –48° Centigrade.

For numerous applications like time resolved spectroscopy, fiber optics diagnostics, quantum cryptography and others, the high repetition rate of the photon counting is requested. The operation of the active quenched and gated APDs at high gate repetition rates is limited by the afterpulsing effects – the dark count rate is increasing with the repetition rate of the gating of the photon counting detector. On Figure 9 there is a plot of the dark count rate of the detector for the gate rates 1 kHz to 1 MHz. The increase of the dark count with the gate frequency is negligible for the room temperature and is small for –48° Centigrade thus making this configuration of a detector attractive for high repetition rate systems. This result is in contrast to the results reported earlier[1], the relatively high operational temperature and a new design of an active quenching and gating circuit are responsible for this improvement. The measurement of the dark count rate increase for high gating repetition rates has been limited by the experimental setup employed. The measurement chain consisting of TAC and Multichannel Analyzer limited the maximum repetition rate to values bellow 1 MHz. Even higher maximum repetition rates are expected to be achievable using the existing active quenching and gating circuit in connection with the EG&G diode operated at temperatures –48° to +30° Centigrade.

6. CONCLUSION

We have investigated in detail the parameters of the EG&G and Fujitsu InGaAs/InP avalanche photodiodes operated in active quenching and gating mode as photon counters in the temperature range –60° to +30° Centigrade. We have optimized the design and construction of the active quenching and gating circuit for operation with these diodes. From the point of view of the dark count rate and afterpulsing, the EG&G diode has been found to be a better candidate. We have found the optimum operating conditions of the diodes. As a result, we did construct a compact all solid state photon counting detector based on the EG&G InGaAs/InP avalanche photodiode C30644E exhibiting the Noise Equivalent Power (NEP) of 7×10^{-16} W/Hz$^{1/2}$ and a timing resolution of 3.2 nanoseconds. The dark count rate is increasing less than twice for the gate on repetition rates reaching 1 MHz. The detection chip was cooled down to –48° Centigrade. This temperature is easily achievable by commercial thermoelectrical coolers. The exact temperature has to be maintained within 0.5 degree Centigrade limits. Sub-nanosecond timing resolution is achievable using the Fujitsu diodes when biasing the chips several Volts above the break voltage at temperatures bellow –65° Centigrade, however, the dark count rate exceeds several MHz and the NEP increases above 1×10^{-15} W/Hz$^{1/2}$ in this setup.

7. ACKNOWLEDGEMENTS

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