

# New materials for photon counting avalanche photodiodes

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## ABSTRACT

The first experimental results acquired on avalanche photodiodes based on III-V materials and operated as photon counters with picosecond timing resolution are reported. The semiconductor structures fabricated on the basis of GaAs, GaP and GaAsP have been operated in a Geiger mode and employed in a photon counting experiment at the wavelengths from near ultraviolet to near infrared. The dark count rates, photon counting sensitivity and timing resolution have been measured for the experimental diode samples for the first time.

**Keywords:** solid state single photon detector, gallium, compound semiconductors, avalanche photodiode

## 1. INTRODUCTION

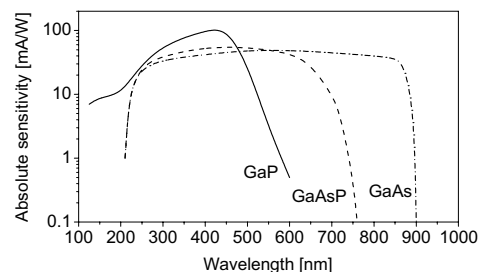
The solid state photon counters with high timing resolution are of interest of numerous electro-optical techniques: laser range finding, optical time domain reflectometry, time resolved spectroscopy, quantum cryptography and others. At present, the most promising technique to detect single photons by 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<sup>1</sup>, 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 an active quenching circuit well adopted for applications listed above<sup>2</sup>. The quantum efficiency corresponds to a silicon, it drops for the wavelengths longer than 1.1  $\mu\text{m}$  and shorter than 0.35  $\mu\text{m}$ . In an attempt to increase the quantum efficiency in the near infrared, the structures based on a germanium doped silicon have been tested. For individual photon detection in the near infrared, the germanium APDs in a cryogenic environment has been employed. 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  $\mu\text{m}$  in the Communication Research Labs., Tokyo, Japan<sup>3,4</sup>. For the telecommunication applications at the 1.55  $\mu\text{m}$  wavelength the thermoelectrically cooled photon counter based on an InGaAs/InP avalanche photodiode has been developed<sup>5</sup>.

For the applications in satellite laser ranging, the increase of a timing resolution of the detector is required. Recent developments resulted in a custom designed APD on silicon having a diameter of 0.2 millimeters in diameter exhibiting a dark count rate below 60 kHz. The APD chip is cooled by a three stage thermoelectrical cooler and enclosed in a miniature evacuated package. The detector is equipped with the electronic compensation of the detection delay dependence on optical signal strength. This way, the detector may be employed for signals of single up to several thousands of photons<sup>6</sup>. The timing resolution of 60 picoseconds FWHM is achieved on single photon signal level. It is the value three times worse than necessary for one millimetre precision required in this application. Additionally, the non-standard data distribution when detecting individual photons at the wavelength above 0.6  $\mu\text{m}$  represents a serious limitation. That is why, new materials for the photon counting detection structures have been investigated. The III-V materials have been selected in an attempt to reach higher timing resolution and standard data distribution. The perspective applications in the ultraviolet are another reason for the III-V materials experiments.

## 2. III-V PHOTON COUNTING AVALANCHE PHOTODIODES

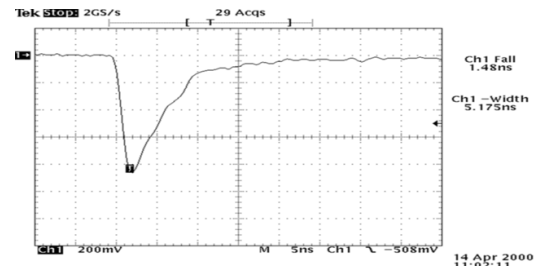
The spectral sensitivity of the GaAs, GaP and GaAsP are plotted on Figure 1. The diodes on GaP are of special interest due to their



**Figure 1:** The spectral sensitivity of GaAs, GaP and GaAsP according to reference 7.

sensitivity in the ultraviolet. All the diodes have been manufactured using a conventional planar technology. The active area of the diode is octagonal with the “diameter” of 350  $\mu\text{m}$ . The GaAs and GaAsP diodes are constructed to be illuminated on an active area, due to the technology reason, the GaP diode is of “reach through” construction.

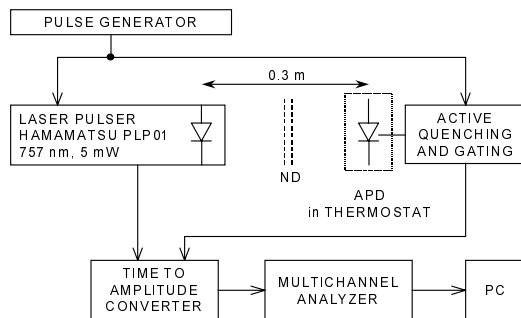
The diodes have been tested in a passive quenching circuit consisting of a serial resistor 1 MegaOhm blocked by a 20 picoFarad capacitor. The example of the output pulse of the GaAsP diode is on Figure 2. The break voltage at a room temperature is 24 Volts with a drift of 15 mV/K. The break voltage of the successful GaAs and GaP diodes was 40 Volts and 24 Volts, respectively. The amplitude of the pulse is one half of the value of bias above the break voltage. It indicates relatively low serial differential resistance of the structure above its break, 50 Ohms typically. It makes the diodes attractive for application as photon counters operated in an active quenching and gating mode. The output pulses parameters were similar for all three diode materials.



**Figure 2:** GaAsP diode output pulse in a passive quenching scheme, diode biased 2 V above break voltage, bandwidth 400 MHz, fall time 1.5 ns, width 5.2 ns.

### 3. EXPERIMENTAL SETUP

In all the following experiments, the diodes have been operated in an active quenching and gating mode, using a circuit developed for silicon photon counting detectors<sup>2</sup>. The block scheme of the test setup is on Figure 3. The time-correlated

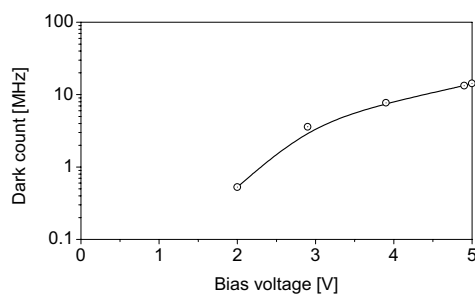


**Figure 3:** Block scheme of the detector test setup, time correlated photon counting experiment.

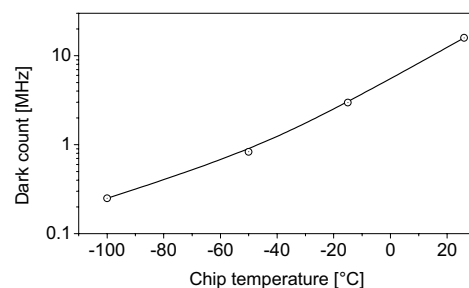
photon counting scheme has been used. The laser diode LD provided optical pulses 32 picoseconds long at 0.757  $\mu\text{m}$ . The signal has been attenuated using the neutral density filters ND. The Active Quenching and Gating Circuit generated the NIM timing pulses. The Time to Amplitude Converter TAC provided the timing resolution of 20 picoseconds per channel. 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. The useful signal detection rate on the single photon level has been used for a rough estimate of the relative detection efficiency in comparison to the silicon based diode.

### 4. EXPERIMENT RESULTS AND DISCUSSION

The dark count rate of the GaAsP avalanche photodiodes as a function of the bias above the break is plotted on Figure 4, the measurement has been carried out with the repetition rate 100 Hz. Considering the diode active area, the dark count rate is in principle comparable to the silicon based SPADs, which is of the order of 1 MHz, 5 V above the break, at the same temperature and active area 100  $\mu\text{m}$  in diameter. The dark count rate can be reduced by diode cooling. On the Figure 5 see



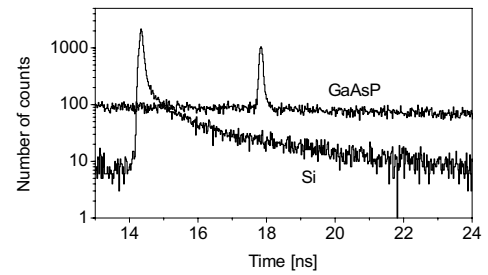
**Figure 4:** Dark count rate of the GaAsP diode as a function of bias above break, diode operated in an active quenching and gating circuit.



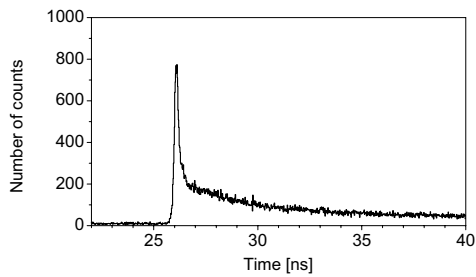
**Figure 5:** Dark count rate of the GaAsP diode as a function of temperature, diode operated in an active quenching and gating circuit, 5 V above the break.

the plot of the dark count rate versus temperature. The decrease of the dark count rate with temperature is rather low in comparison to silicon or germanium diodes, one order of magnitude per 60 K. The timing resolution has been measured in an arrangement described on Figure 3. For comparison purposes, the reference APD on silicon (SPAD<sup>2</sup>) has been employed. The results are summarized on Figure 6, the photon counting time response of the GaAsP diode (upper curve) and silicon SPAD (lower curve). Note equal width of both the distributions and a highly non-symmetrical data distribution (tail) of the silicon SPAD in contrast to a nearly ideal normal distribution of the GaAsP diode. The timing resolution 112 psec FWHM for both samples has been limited by the experimental chain. The single photon detection efficiency has been found to be in the range 0.1 to 1 % at the testing wavelength. The detection probability is a product of two probabilities: probability of generating a carrier and probability of the avalanche triggering. According to Figure 1, the first probability should exceed 10%, thus the limiting factor in our detector photon counting sensitivity was the low probability of avalanche triggering. This parameter may be improved by the diode structure design and optimization specifically for photon counting purposes.

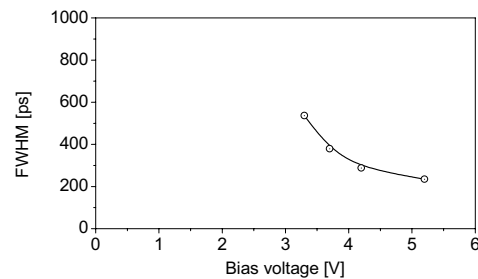
The example of the timing resolution data of the GaAs photon counter is on Figure 7. The diode has been biased 5 Volts above the break. The dark count rate of 20 MHz has been observed at +25°C. Comparing to the GaAsP diode, the



**Figure 6:** Timing resolution of the GaAsP and silicon photon counters operated 5 V above their break voltage, FWHM = 112 ps for both diodes. Note high non-symmetry of the silicon diode data distribution.

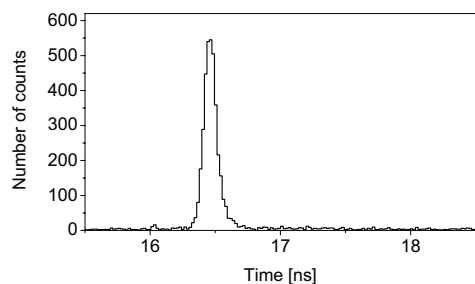


**Figure 7:** Timing resolution of the GaAs diode operated as a photon counter operated 5V above the break voltage, FWHM = 230 picoseconds.

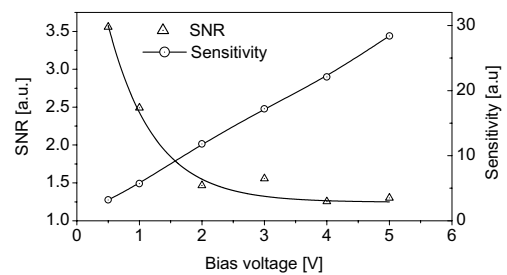


**Figure 8:** Timing resolution of GaAs diode operated as a photon counter versus bias above break voltage.

timing resolution is more than twice worse and the data distribution exhibits a significant non-symmetric, the percentage of the data points in the tail of the distribution exceeds 70 %. This fact inhibits the application of GaAs diodes for laser ranging purposes. The dependence of the timing resolution on the diode biasing is plotted on Figure 8.



**Figure 9:** Timing resolution of the GaP diode operated 5 V above the break voltage as a photon counter, FWHM = 110 ps. Note good symmetry of the data distribution.



**Figure 10:** Sensitivity and SNR of the GaP diode based photon counter versus bias above the break.

The GaP diode timing properties are demonstrated on Figure 9, where the time correlated photon counting results are plotted. Although the test wavelength has been outside the main sensitivity of the material, see Figure 1, the residual sensitivity permitted to carry out the measurements. The photon counting probability was of the order of 0.01 % in this case.

The timing resolution FWHM of 110 picoseconds has been obtained, the data distribution is quite well symmetric and close to normal one. The diode has been biased 5 Volts above the break, the dark count rate of 6 MHz has been measured. The relative sensitivity and Signal to Noise Ratio SNR versus voltage above the break is plotted on Figure 10.

## 5. CONCLUSION

The avalanche diode structures operational as single photon detectors with picosecond resolution on the basis of the GaAs, GaP and GaAsP materials have been designed, developed and tested. This is to our knowledge the first published attempt to develop a photon counting avalanche photodiode on the basis of these materials. The timing resolution FWHM of 112, 275 and 110 picoseconds for the diodes on GaAsP, GaAs and GaP, respectively, has been obtained. The dark count rate comparable to existing silicon avalanche photodiodes has been measured. The GaAsP and GaP photon counters exhibit time correlated photon counting data distribution very close to ideal normal distribution in the near infrared wavelength. It is expected, that further tuning of the diode structure and its optimization for photon counting will result in a detector with timing resolution better than silicon detectors and will provide a nearly ideal data distribution in the near infrared with the detection efficiency reaching 10 %.

## 6. ACKNOWLEDGEMENTS

This work has been completed with a partial support of the grant of the Grant Agency of the Czech Republic № 102/00/0820 and of the framework of CTU research projects MSM 210000015.

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