# Temperature characteristics of silicon avalanche photodiodes

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## ABSTRACT

The paper presents the results of studies on temperature dependence of such parameters as a dark current, noise current, gain, noise equivalent power and detectivity of silicon epiplanar avalanche photodiodes developed at the ITE. The photodiode reach-through structure is of an $n^+$-p-$\pi$-$p^+$ type with an under-contact ring and a channel stopper. The temperature range was stretching from –40 C to +40 C. Specially developed for this purpose an automatic system for low noise measurements was used. A two-stage micro-cooler with a Peltier's element was applied to control and stabilise the temperature of measured structures.

**Keywords:** silicon avalanche photodiode, temperature dependence

## 1. INTRODUCTION

The widespread use of semiconductor sensors, and recently those containing silicon avalanche photodiodes (APDs), in great variety of application made their reliability to work in a wide range of temperature of a paramount importance. Since many phenomena in avalanche photodiodes are especially prone to temperature changes, the knowledge of temperature dependence of avalanche photodiode parameters is very essential for application goals. The parameters in question are; a gain (sensitivity), dark and noise currents and conditioned by them noise equivalent power or detectivity

The influence of temperature on properties of nonavalanche silicon photodiodes is apparent in photodiode dark current dependence on temperature. In a well-designed and correctly fabricated photodiode of the PIN type (and nowadays most of developed and manufactured photodiodes are such) this dark current is mainly of the generation-recombination nature and flows through a space charge region of the structure. With the increase of temperature (for T <70C) the dark current increases proportionally to the expression $\exp(-E_g/2kT)$, where $E_g$ is an energy gap, k is the Boltzmann's constant, T is the absolute temperature in Kelvin. As the noise of a PIN photodiode is of the shot kind so its noise current is $I_N = (2qI_0\Delta f)^{1/2}$, where q is the charge of an electron, $I_0$ is a dark current, $\Delta f$ is a detection bandwidth.

Unlike the dark current, the sensitivity (quantum efficiency) of silicon photodiodes hardly depends on temperature for the radiation of wavelengths that is used in majority of applications ($\lambda$ < 950 nm).

In the case of avalanche photodiodes, the temperature dependence of their operating parameters is a bit more intricate. A photocurrent gain (and also conditioned by it a total sensitivity), dark and noise currents, all these parameters depend strongly on operating temperature especially when avalanche photodiodes are biased near the avalanche breakdown voltage. It is due to the strong temperature dependence of electron and hole ionisation coefficients. The higher temperature, the lower are electron and hole ionisation coefficients, thus the lower is gain at a given bias. By the same token, the higher temperature, the higher operating voltage needed to attain a given gain and consequently higher photodiode dark and noise currents. However, the character of temperature relationships of dark currents strongly depends on whether a dominant component of the dark current (of generation-recombination nature) is the surface or bulk component at the given bias voltage. If the surface component (that doesn't flow throughout the avalanche region) dominates then the temperature dependence of the noise and the dark currents of APDs is similar to the PIN photodiode dependence. If the dominant component is the bulk current (that is multiplied in the avalanche region similarly as photocurrent is) the temperature dependence of dark is conditioned by temperature dependence of electron and hole ionising coefficients. In this case the noise current (avalanche noise current) hardly depends on temperature for the bias voltages before the breakdown voltage. It is due to the fact that the avalanche noise depends on the ratio of hole to electron ionising coefficients which in turn hardly depends on temperature [1-6].

As the result, the temperature dependence of the noise equivalent power NEP (or detectivity D)- the parameter that best characterises detector performance- most often stems from temperature dependence of gain at a given operating voltage or from temperature dependence of an operating voltage that is needed to sustain a fixed gain.

## 2. THE RESEARCH METHODS AND ATTAINED RESULTS

The 3mm silicon epiplanar avalanche photodiodes with reach-through structure of an $n^+$-p-$\pi$-$p^+$ type, developed at ITE were studied [7,8]. For temperatures in the range of -40C ÷ +40C, the following measurements were conducted; dark current $I_0$,

photocurrent (gain M) at $\lambda$ = 820 nm and noise current $I_N$ (in the unit band of detection $\Delta f$ = 1 Hz) as the function of avalanche photodiode bias voltage $V_R$.
The measurements were done in the automatic electronic set-up, shown in fig. 1, with a transimpedance amplifier for low noise measurements. Photodiodes were put into a light–tight holder containing a two-stage micro-cooler with Peltier's element, shown in fig. 2.

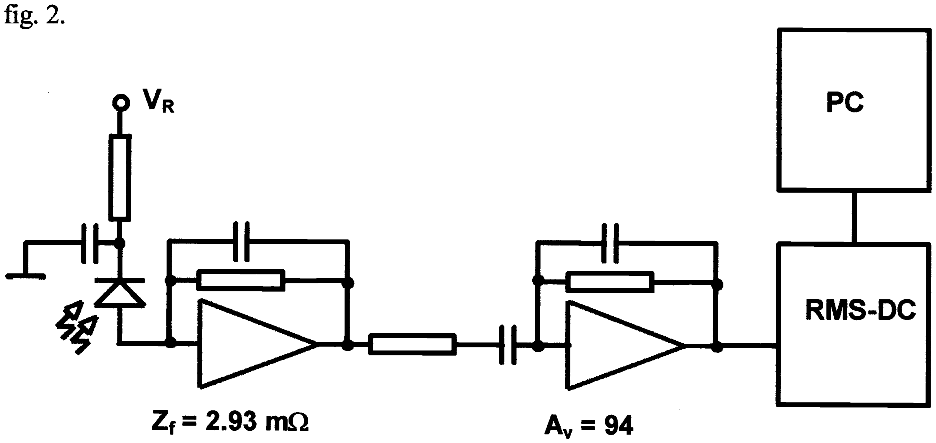


Fig. 1 Block diagram of the noise measurement setup.

The noise current of a photodiode in the above set is calculated from the formula:

$$I_N = \frac{\sqrt{(V_n^{\,2} - V_0^{\,2}) / \Delta f}}{Z_f A_v}$$

where: $V_n$ - output voltage of the RMS-DC converter with a photodiode connected to it, $V_0$ - output voltage without a photodiode (background noise voltage), $Z_f$ - transimpedance of the first stage, $A_v$ - amplification of the second stage, $\Delta f$ - bandwidth.

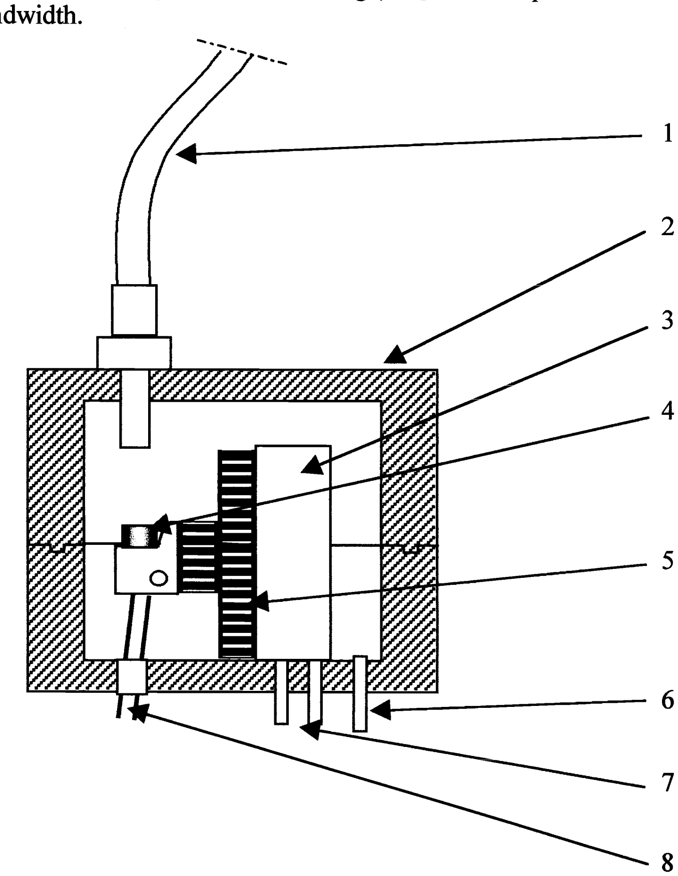


Fig. 2 The light -tight holder for a photodiode

1. Optic fibre
2. Light-tight screen
3. Water cooler
4. Holder for a photodiode
5. Two-stage cooler
6. Dry gas pipe
7. Water pipes
8. Photodiode electrical leads

The system of controlling and stabilising temperature ensured the 0.1C precision of setting and temperature control.

On the basis of measured characteristics the following parameters were determined:

- $\alpha_T$ temperature coefficient of operating voltage $V_R$ changes (or avalanche breakdown voltage changes) $\alpha_T = V_{R2} - V_{R1} / T_2 - T_1$
- a gain sensitivity to ambient temperature changes $1/M \times dM/dT$
- temperature dependence of noise equivalent power - NEP = $I_N/(S_{\lambda 0} \times M)$, where $S_{\lambda 0}$ –primary sensitivity (M = 1)
- normalised (to the unit active area of a detector-1 $cm^2$) detectivity $D = A^{1/2}/NEP$ where A is the photodiode active area in $cm^2$.

Bellow the samples of obtained results are presented. In fig. 3-5, for different temperatures, the bias voltage dependence of the gain, dark current, and noise current are shown, while in fig. 6 and 7 noise current and NEP in function of gain for different temperatures.

The temperature dependence of NEP and detectivity at M = 100 and at M = $M_{opt}$ is depicted in fig. 8 and 9. At $M_{opt}$ the signal to noise ratio achieves maximum value, it means NEP has its minimum value.

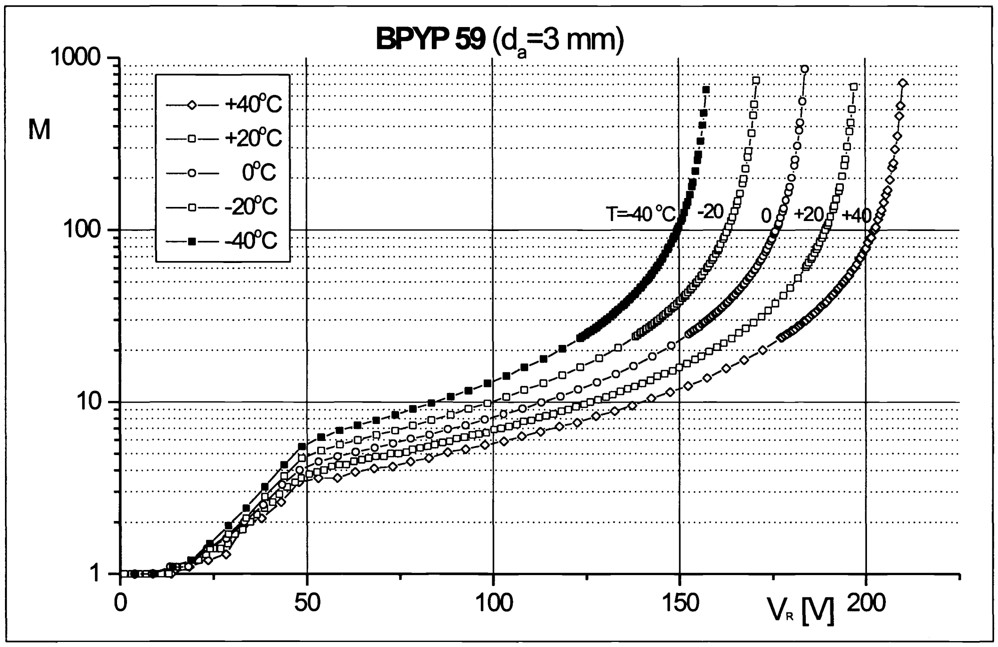


Fig. 3 An example of temperature dependence of gain versus bias voltage characteristics. The 3 mm diameter avalanche photodiode (BPYP 59)

As it is seen in fig. 3, to maintain constant gain during the temperature changes it is necessary to change a bias voltage. The temperature coefficient of voltage changes $\alpha_T$ typically amounts to the value of 0,65 V/C (see table 1)

The feature of the $I_0(V_R)$ function points to the fact that for $V_R < V_{BR}$ ($V_{BR}$ –avalanche breakdown voltage) the dominant kind of current is the surface current. For $V_R \approx V_{BR}$ , the dominant kind of current is the bulk current. The temperature coefficient of $V_{BR}$ changes, much like for $V_R$, typically amounts to 0,65 V/C

The $I_{N0}(V_R)$ dependence for voltages below value of 70 V is conditioned by the change of the level of noise in the transimpedance amplifier that results from the change in the value of structure capacitance. In that case the noise current hardly depends on temperature for the voltages lower than the breakdown voltage.

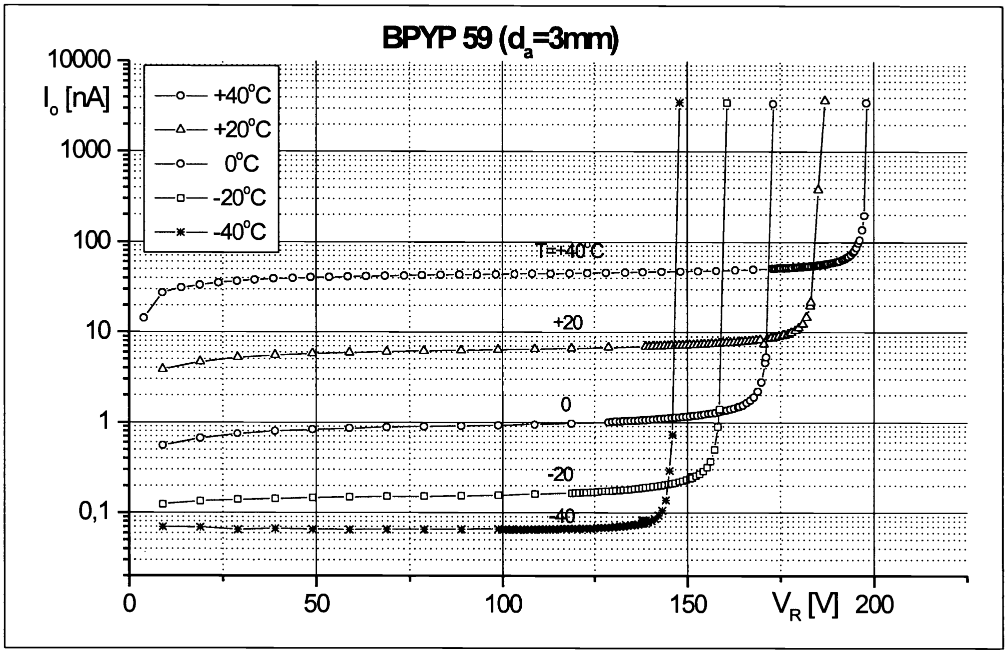


Fig.4 An example of temperature dependence of dark current versus bias voltage characteristics. The 3 mm diameter avalanche photodiode (BPYP 59)

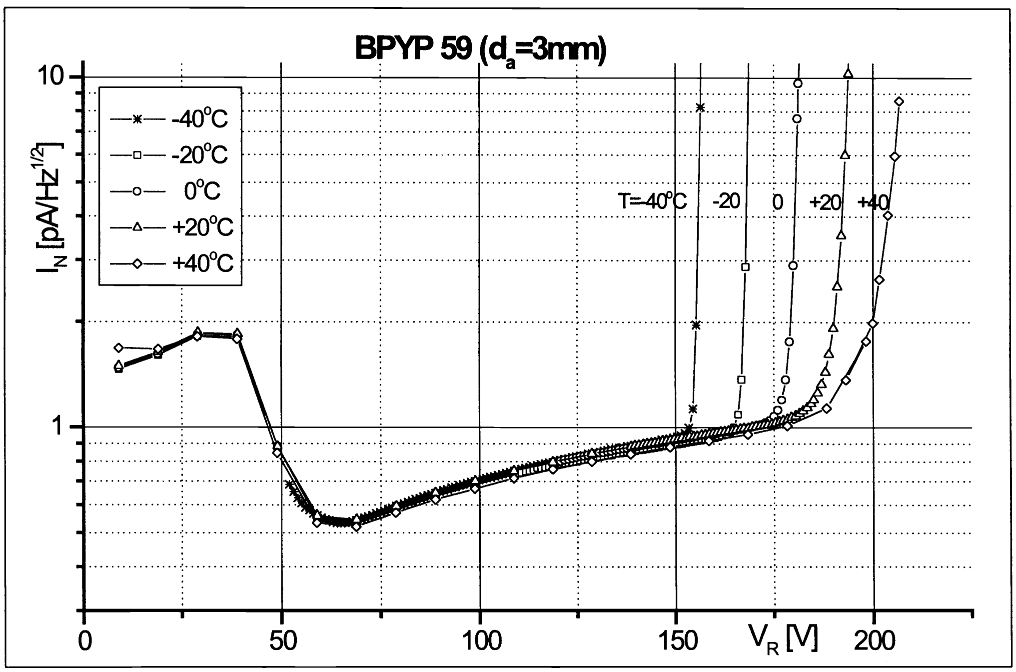


Fig. 5 An example of temperature dependence of noise current versus bias voltage characteristics. The 3 mm diameter avalanche photodiode (BPYP 59)

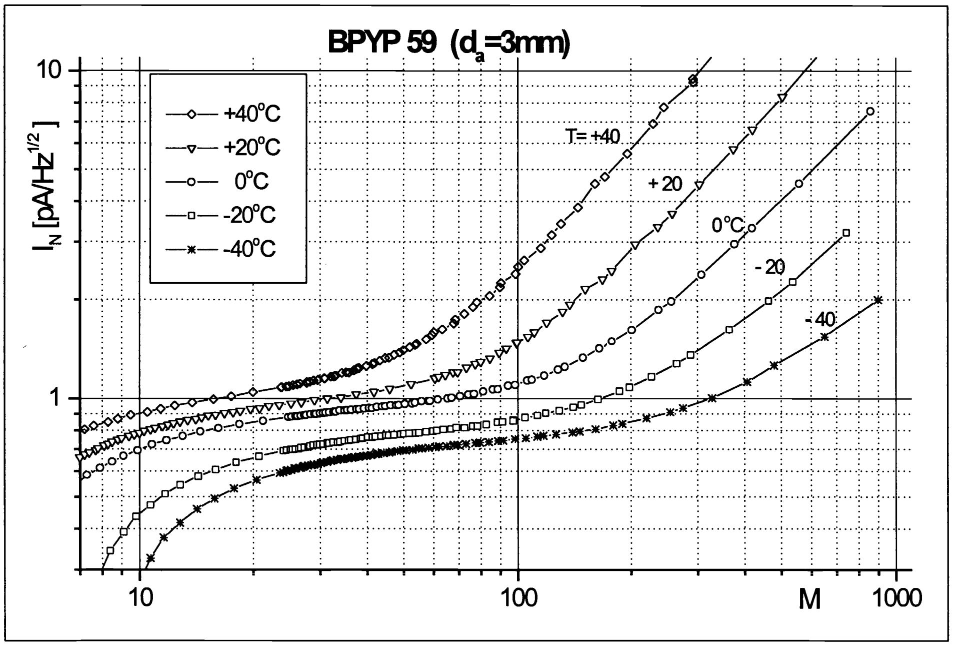


Fig. 6 An example of temperature dependence of noise current versus gain characteristics.
The 3 mm diameter avalanche photodiode (BPYP 59)

The $I_{N0}(M)$ relation (fig. 6) enabled to calculate the NEP(M) dependence for different temperatures (fig. 7) as well as to determine the value of $M_{opt}$, at which the NEP attains the minimum value (fig. 8) and detectivity its maximum (fig. 9).

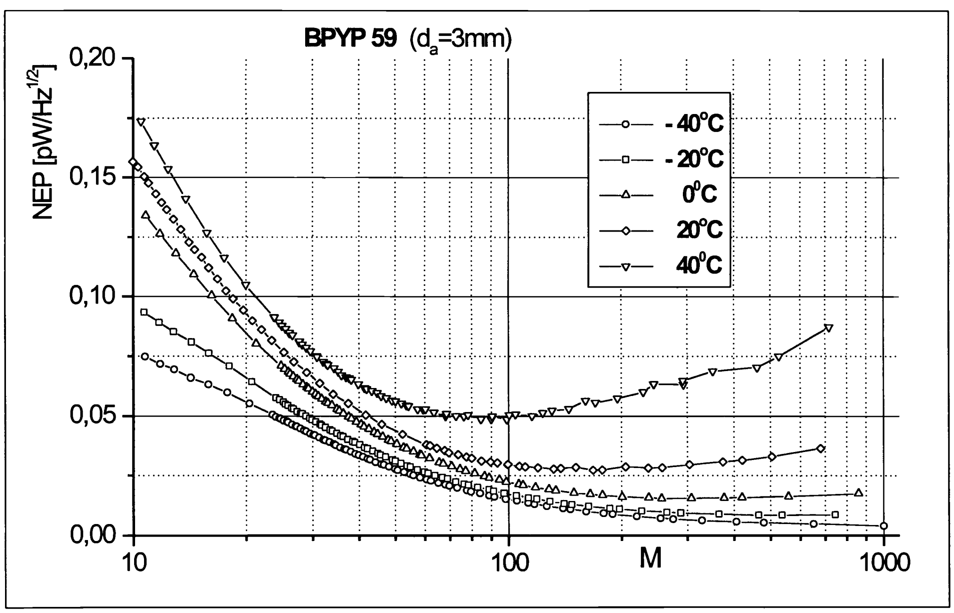


Fig. 7. An example of temperature dependence of noise equivalent power versus gain characteristics.
The 3 mm diameter avalanche photodiode (BPYP 59)

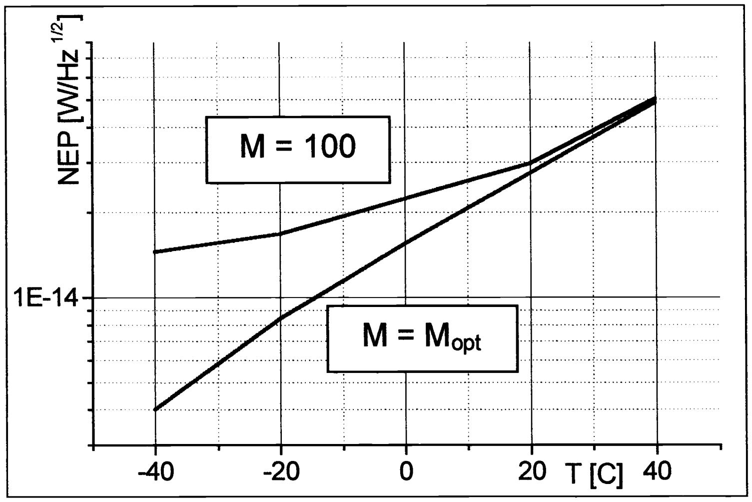


Fig. 8 An example of temperature dependence of noise equivalent power at M = 100 and at M = $M_{opt}$.
The 3 mm diameter avalanche photodiode (BPYP 59)

The increase of noise current with temperature at M = cons. is due to the fact that to sustain the fixed gain the bias voltage has to be increased.

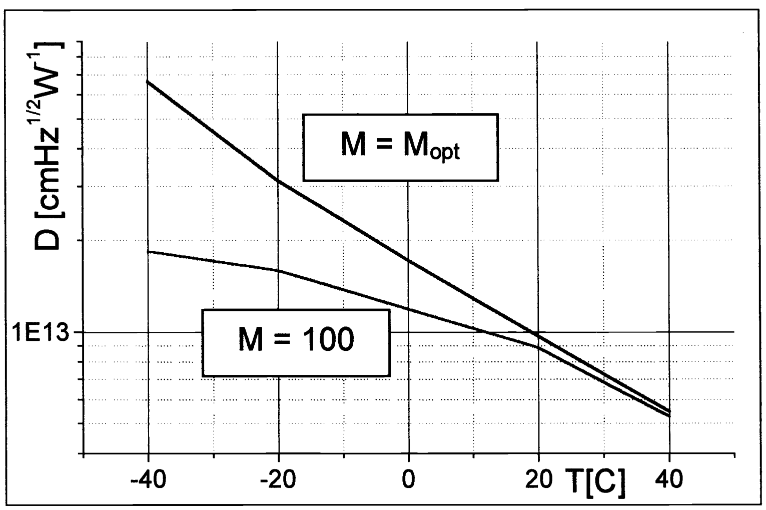


Fig. 9 An example of temperature dependence of detectivity at M = 100 and at M = $M_{opt}$.
The 3 mm diameter avalanche photodiode (BPYP 59)

The lower the temperature, the lower the noise equivalent power at M = cons. and at the same time the higher is the optimal gain ensuring the very low value of NEP.

In fig. 10 there is relative dependence of gain on temperature changes (1/M×dM/dT). near 24 C.
The most important values of temperature coefficients are put together in table 1.
Relative changes of gain are - 6.5 %/C for M = 100 close to ambient temperature of 24C.

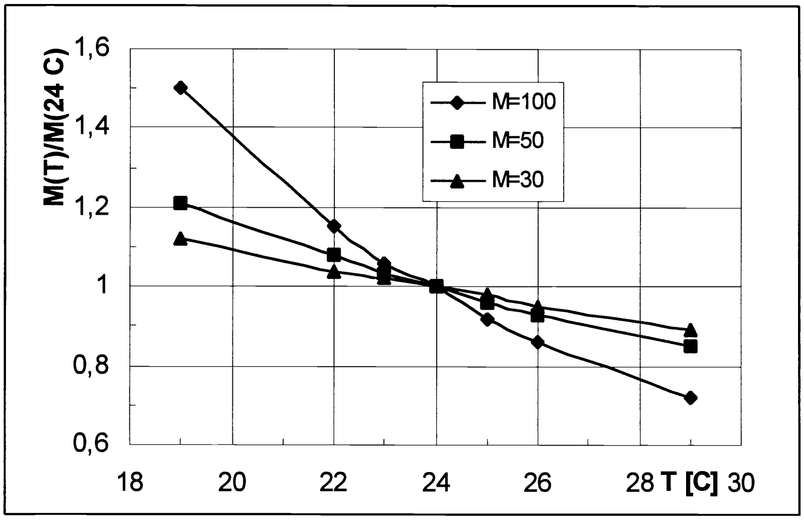


Fig. 10 The relative temperature dependence of gain near the temperature of 24 C

Table 1 The values of temperature coefficients of the BPYP 59 silicon avalanche photodiodes (of the 3 mm diameter)

| Parameter | Symbol | Unit | Value | | | Test conditions |
|---|---|---|---|---|---|---|
| | | | Min. | Typ. | Max. | |
| Temperature coefficient of operating voltage changes | $\alpha_T$ | V/C | 0,6 | 0,65 | 0,7 | M=100 |
| $1/M \times dM/dT$ | | %/C | | -1,9 | | M=30, $T_0$=24C |
| $1/M \times dM/dT$ | | %/C | | -3,3 | | M=50, $T_0$=24C |
| $1/M \times dM/dT$ | | %/C | | -6,5 | | M=100, $T_0$=24C |

## 3. SUMMARY

Designed and fabricated at the ITE, 3 mm diameter silicon avalanche photodiodes were characterised with respect to the temperature dependence of their parameters in the temperature range of – 40 + 40C. A photodiode structure is of an $n^+$-p-$\pi$-$p^+$ reach-through type with an under-contact ring and a channel stopper.

The characteristics of gain, noise and dark currents versus bias voltage for different temperatures were measured. The temperature coefficient of operating or breakdown voltage changes was determine as well as a "sensitivity" of gain to small ambient temperature changes. The design of the examined avalanche photodiodes ensures relative changes of gain lower than 10%/C for M = 100 close to the ambient temperature of 24C.

The values of the noise equivalent power and detectivity as a function of temperature were calculated. The presented results show that these photodiodes attain very low values of the noise equivalent power NEP, even below $10^{-14}$W/Hz$^{1/2}$ for temperatures lower than - 20 C, what corresponds to the detectivity of D > $3\times10^{13}$ cmHz$^{1/2}$W$^{-1}$. For these temperatures, the high values of optimum gain $M_{opt}$ > 200 are obtained, the optimal gains can be as high as 1000. For example, at T = - 40C, NEP($M_{opt}$ ) = $2\times10^{-15}$W/Hz$^{1/2}$. For T ≤ 20 C: NEP < $3\times10^{-14}$W/Hz$^{1/2}$ (detectivity D > $10^{13}$ cmHz$^{1/2}$W$^{-1}$).

For ITE avalanche photodiodes of the smaller diameters (0.3, 0.5, 0.9, 1.5mm) the noise currents and resulting from them NEP values are respectively lower, however the character of the temperature dependence remains the same.

The knowledge of the temperature dependence of photodiode parameters enables to design so called intelligent sets biasing APDs. In such sets a bias voltage is automatically regulated to ensure a fixed value of the gain or of the noise current in a specified range of temperatures. The temperature characterisation of avalanche photodiodes also can be used in developing the detection module containing an APD and micro-cooler with a Peltier's element lowering and stabilising the operating temperature.

## 4. ACKNOWLEDGEMENTS

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