Characterization of high performance PbS photodetectors

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Dark noise plays an important role in electronic devices, especially in detectors. Performance of infrared detectors is reflected by parameters such as detectivity and specific detectivity, strongly related to the noise spectral density. This work summarizes the results on characterization of high-performance PbS photo detectors, using a certification pending method developed by the laboratory, in agreement to the standard ISO/CEI 17025:2005. The method is validated for a resistor of known resistance, by comparing the Johnson thermal noise using two different methods: first, the fast Fourier transform measured with a Stanford Research Systems SR785 Spectrum Analyzer and second using a Stanford SR830 lock-in amplifier which measures the rms noise for a certain frequency. We studied the influence of physical dimensions on the performance of thin film polycrystalline PbS photoresistors in the planar geometry. Measurements were performed to compare the dark noise of PbS photoresistors with that in high quality metal thin film resistors. The laboratory setup used for the measurements is appropriate to accurately determine typical parameters of infrared detectors such as spectral responsivity, blackbody responsivity, specific detectivity, and noise spectral density.

1. Introduction

Noise measurements provide a valuable diagnostic tool for the evaluation of the electronic and optoelectronic devices and their long term performance [1]. Random low frequency noise arises from many physical processes, some of which are understood and some which are not. Among them, the best understood type of noise is the Johnson-Nyquist thermal noise that is generated by the equilibrium fluctuations of the electric current inside an electrical conductor, which happens regardless of any applied voltage, due to the random thermal motion of the charged carriers. Shot noise is not normally expected to occur in simple resistors, being associated with electronic devices where some potential barriers exist, such as tunnel or Schottky diodes or p-n junctions.

The 1/f noise or flicker noise has a frequency spectrum such that the spectral power density is proportional to the reciprocal of frequency, dominating the noise spectrum below about 100 Hz. There is no universally accepted theory for this type of noise even if it has a universal nature, being observed in phenomena from the microscopic to the astronomical scale. It occurs in many physical, biological and economical systems. This kind of noise tends to be ohmic, although the proportionality constant is not related to the resistance of the device. There is also the generation-recombination noise type, which is associated with the trapping and emission of charges from deep traps and depends like $\sim 1/f^2$ for frequency values larger than the characteristic frequency of the dominating process. There are few reports on the low frequency behavior of noise in PbS photoresistors, the difficulty lying in the interpretation of

the results and in the notorious difficulty of making low noise measurements.

2. Experimental

For the experiment we employed the equipment for complex characterization of samples and devices of the newly set up, certification pending, "Laboratory for characterization of IR detectors" to the EU Standard - ISO / IEC 17025:2005, within the National Institute of Materials Physics in Bucharest.

Measurements for the responsivity of detectors were made using the OL 750 radiometric system including a high intensity light source, mechanical chopper and PC-controlled data acquisition system.

For dark noise spectral density measurements we used a low noise SRS voltage preamplifier SR 560 in connection with a low frequency SRS electrical spectrum analyzer SR 785 and respectively SRS Lock-in amplifier SR 830.

The responsivity $R_{detector}$ of a photoresistor is given by

$$R_{detector} = \frac{V_a}{P_{inc} S}$$

[V/W], where V_a is the electrical signal generated by the detector under test and measured across the load resistance R_L, P_{inc} [W/cm^2] is the irradiance and $S = L \cdot w$ is the illuminated area.

The specific detectivity D* is defined as

$$D* = \frac{\sqrt{S}}{NEP} = \frac{\sqrt{S} \cdot R_{detector}}{N}$$

[cmHz$^{1/2}$/W] where NEP is noise equivalent power [$W/\sqrt{Hz}$] and N is noise spectral density measured in $V/\sqrt{Hz}$.

The method we developed for measuring the spectral noise density is validated by comparing the $\sqrt{4kTR}$ Johnson spectral noise density measured by two different methods: first, given by the Fourier transform of the signal measured by the spectrum analyzer SR 785 and second using the lock-in amplifier which is measuring the signal at a certain frequency.
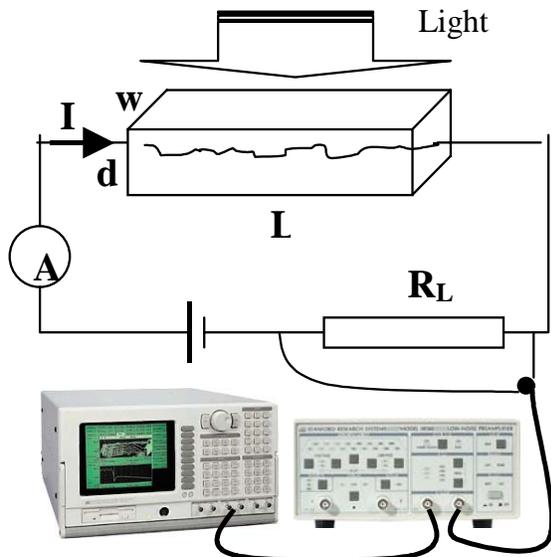

Fig. 1. Typical layout for characterizing the photoresistor.

It is a known fact that performing noise measurements is not an easy task to complete. Special precautions must be taken and accurate measurement methods must be developed and observed.

Typical measurements are performed using the SRS low noise voltage preamplifier SR 560 on x1000 and x10000. Dark noise spectral density is measured using the SR 785 in the power spectrum (PS) mode. The photosignal and the spectral noise density signal are collected from a load resistor R_L as in Fig. 1.

The thin film polycrystalline PbS photoresistors were prepared by the Chemical Bath Deposition method [2].

3. Results and discussion

We characterize two PbS thin film photoresistors in the planar geometry. The two resistors are obtained under similar deposition conditions, the film thickness being 0.27 μm. For the first photoresistor the illuminated area is 1×1 mm^2 while the second detector has a larger area of 5.5×6 mm^2.
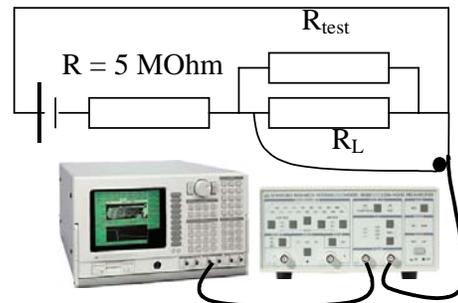
(a)
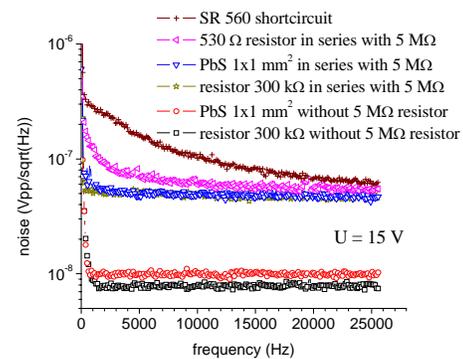
(b)

Fig. 2(a). Layout for validation of the noise measurement setup and (b) experimental spectral noise density measured with and without a current limiting resistance.

The corresponding sheet resistance is 330 kOhm/□ for the first case and 1750 kOhm/□ in the second case, respectively. If the thin film would be perfectly homogeneous the sheet resistance should be the same in both cases. The fact that it is larger for the larger area photodetector indicates that the effects of the inhomogeneities inherent to the polycrystalline nature of the material on the current flow are significant. The lateral linear current density dI/dw is not uniform across w, effectively short-circuiting about 80 % of the illuminated area of the device for the large area device.

In order to validate the noise measurement method we measure the very low signal given by the thermal noise using the same measurement head. However, to avoid the 1/f noise contribution it is necessary to decrease the current in the circuit by adding a resistor of a high resistance, here 5 MOhm, in series with the resistor under test, as in figure 2. The test resistor R_{test} has a resistance much lower than the load resistor, here 530 Ohm compared to 47 kOhm.

The corresponding thermal noise is 3 nV/Hz$^{1/2}$ and is clearly seen in Fig. 2 (b) where the two plots at the bottom represent the measured noise spectra for the low noise voltage amplifier in short-circuit and for the 530 Ohm test resistance using the layout in Fig. 2(a). The total measured noise in the latter case is:

$$N_{test\ resistance} = \sqrt{N^2_{SR\ 560\ shortcircuit} + N^2_{thermal\ 530\ Ohm}} \quad where$$

$N_{thermal\ 530\ Ohm} = 2 \cdot \sqrt{4kTR}$ nV/$\sqrt{Hz}$ since we use Vpp units.

Fig. 2(b) also shows that when the limiting 5 MOhm resistance is used as in the layout of Fig. 2(a) the noise measured on a test resistance of 300 kOhm and on the PbS thin film photoresistor of area 1x1 mm^2, with a similar dark resistance, are comparable and limited by the corresponding thermal noise. However, it is also evident from Fig. 2 (b) that when we make the noise measurement using the layout in Fig. 1 the 1/f noise measured on the 1 x 1 mm^2 PbS photoresistor is 1.7 times larger than that measured on the 300 kOhm resistor and dominates the noise spectrum for frequencies below 3.5 kHz in both cases.
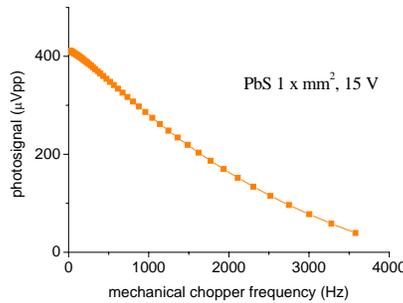

Fig. 3. Temporal response of the photosignal for the 1x1 mm^2 PbS photodetector. The applied bias is U=15 V.

Fig. 3 shows the temporal response of the PbS photosignal as a function of the frequency of modulation of the mechanical chopper. We extract from Fig. 3 the upper limiting frequency defined as the frequency for which the amplitude of the photosignal drops 20 dB below its maximum value (see SR 61920/2004) f_{2u} = 3.5 kHz. It results that under these conditions, i.e. when the external bias is applied on the PbS photoresistor in series with the 45 kOhm load resistance and with 15 V applied bias, the dark noise spectrum is dominated by the 1/f noise.

Regarding the photoresistor as a bar-shaped uniform thin film with a length L and cross section $A = wd$, where w is the width and d is the layer thickness as in Fig. 1, one can find that the small signal component of the photovoltage on the load resistance can be expressed as

$$\Delta v_L(t) = V_A \cdot \left[\frac{R_L}{(R_L + R_{dark})}\right] \cdot \left[\frac{R_{dark}}{(R_L + R_{dark})}\right] \cdot \left[\frac{\left(\frac{\Delta\sigma}{\sigma_0}\right)}{\left(1 + \left(\frac{R_L}{(R_L + R_{dark})}\right) \cdot \left(\frac{\Delta\sigma}{\sigma_0}\right)\right)}\right] \quad (1)$$

where σ_0 is the dark conductivity and $\Delta\sigma$ is variation of conductivity due to illumination. R_{dark} is the dark resistance of the photoconductor.

It is worth mentioning that the maximum of output signal as given in eq. (1) is obtained by choosing the load resistance in series with the photoresistor to have the same

value as the dark resistance of the photoresistor, $R_L = R_{dark}$.

If we assume in our case $R_L \ll R_{dark}$, then the photosignal [V] can be expressed by

$$\Delta v_L \cong V_A \cdot \frac{R_L}{R_{dark}} \cdot \frac{\Delta\sigma}{\sigma_0} \quad (2)$$

As a consequence the responsivity is given by

$$R_{detector} \approx V_A \cdot \frac{R_L}{R_{dark}} \cdot \frac{\Delta\sigma}{\sigma_0} \cdot \frac{1}{P_{inc} \cdot S} \quad (3)$$

We should mention here that we refer to the illuminated area $S = L \cdot w$ whereas $A = d \cdot w$ is the transversal area through which the current flows as in Fig. 1.

Introducing σ, R_{dark} and S in the eq. (3) we obtain:

$$R_{detector} = V_A \cdot R_L \cdot \frac{q\Delta n(\mu_e + \mu_h)}{P_{inc}} \frac{w_1 \cdot d}{w_2 \cdot L^2} \quad (4)$$

where w_1 is the equivalent width for the current transport and w_2 is the width of the illuminated area.

From eq. (4) we conclude that for a perfectly homogeneous thin film of thickness d in a planar geometry, i.e. when $w_1 = w_2$, the responsivity $R_{detector}$ is directly proportional with the applied bias, V_a, inversely proportional with L^2 and does not depend on w. However, if for a larger area device the current flow is short-circuited by a path of effective width $w_1 < w_2$ the apparent responsivity decreases with the factor w_1/w_2.

If the photodetector dark noise is limited by the thermal component then $N = \sqrt{4kT\rho_{square}\frac{L}{w}}$ [V/Hz$^{1/2}$],

where $\rho_\square$ is the sheet resistance per square and does not depend on the applied bias. If it is dominated by its 1/f component it is still proportional with $\rho_\square^{1/2}$ [3-4] but also with the DC current flowing through the resistor. When the photoconductor resistance is larger, the corresponding smaller current noise fluctuations in the photoresistor generate a smaller voltage noise on the load resistance of 47 kOhm. For the devices studied here the small area device shows good performance, having a responsivity better than 70000 V/W (λ=2400 nm, V_A=15 V, 600 Hz) and a corresponding detectivity of 2.3 x 10^{10} $cm\sqrt{Hz}/W$ for the same applied bias and wavelength, the noise being dominated by the 1/f component. This value can increase to 1 × 10^{11} $cm\sqrt{Hz}/W$ by choosing an optimized load resistance and bias. Fig. 4 shows the spectral responsivity of both small area and large area devices. For the large area device the responsivity is 1100 V/W (λ=2400 nm, V_A=116 V), much lower than the value of 16400 V/W expected from eq. 4 for a homogeneous thin film with $w_1 = w_2$. The detectivity for an applied bias of 74 V is 3.7 × 10^9 $cm\sqrt{Hz}/W$ (400 Hz).
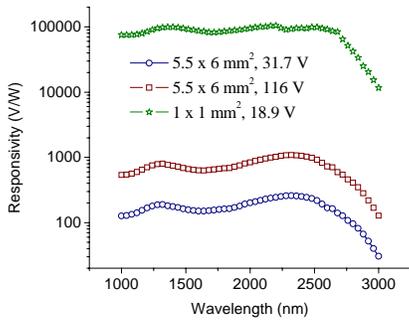
Fig. 4. Spectral responsivity for small area and large area PbS photoresistors.

An explanation for the fact that the responsivity depends on the size of the square photoresistors can be given considering that the current does not flow uniformly through the transversal area. This is a plausible explanation having in mind the non-uniform structure of the polycrystalline PbS. Current may flow from a grain to the next one choosing the smallest resistivity path. This will explain also the difference in the value of the resistance determined for PbS photoresistors of different square dimensions, but made of layers with the same thickness.

Fig. 5 presents the dependence of the photosignal on the applied bias V_A, showing that it is linear and well described by the dependency given in eq. (4), with no effects of velocity saturation for this range of applied electric fields.
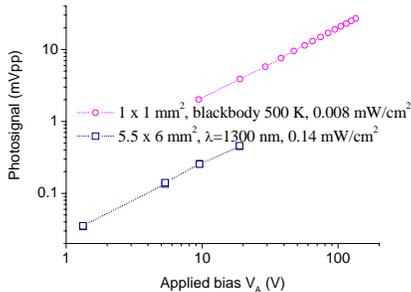

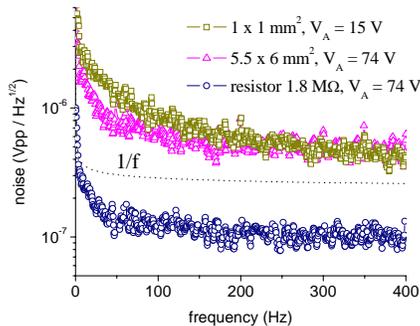*Fig. 5. Photosignal of PbS photoresistors vs. applied voltage V_A.*

Fig. 6. Noise spectra for the large area detector in comparison with a simple resistor with a resistance equal to the dark resistance of the photodetector.

Fig. 6 shows the dark noise spectra of the large area detector in comparison with a metal film resistor having a resistance equal to the dark resistance of the PbS photoconductor and with a small area PbS photodetector, evidencing the 1/f component for a DC current comparable with the case of Fig. 2(b) when the PbS 1×1 mm^2 is biased in the layout of Fig. 1.

The constant of proportionality between the 1/f noise measured on the load resistance of 47 kOhm [V/Hz$^{1/2}$] and the DC current is 5-6 times larger for the small area device in comparison with the large area photoresistor due to the above mentioned inhomogeneities that increase the resistance in the latter case. The 1/f noise of the PbS large area device is 5 times lower than the 1/f noise of a metal resistor with a similar resistance (1.8 MOhm). If the PbS thin film would be homogeneous over the entire deposited area, the dark noise in a square of polycrystalline PbS material is of the same order of magnitude as the one found in commercially available metallic resistors with the same resistance of 300 kOhm.

3. Conclusions

We report results on characterization of high-performance PbS photo detectors, using a certification pending method developed by the laboratory, in agreement to the standard ISO/CEI 17025:2005. The method is validated for a resistor of known resistance by measuring the Johnson thermal noise using two different methods: first, the Fourier transform measured with a Stanford Research Systems SR785 Spectrum Analyzer and second employing a Stanford SR830 lock-in amplifier which measures the rms noise for a certain frequency.

Due to the non-uniform structure of the polycrystalline PbS thin film, the performance of the photoresistors drastically decreases compared to the theoretical predictions for large area devices. Smaller area devices show the best performance, e.g. 1mm x 1mm devices have a responsivity of 90000 V/W (18.9 V) and detectivity of 2.3×10^{10} $cm\sqrt{Hz}/W$ (15 V) whereas devices of 5.5×6 mm^2 have significantly poorer performance. They have a responsivity of 1100 V/W (116 V) and a detectivity of 3.7×10^9 $cm\sqrt{Hz}/W$ (74 V). The sheet resistance of a 1 x 1 mm^2 square device is 6 times smaller than for a 5.5×6 mm^2 photoresistor. We attribute this behavior to the effect of the inhomogeneities in the structure of the polycrystalline PbS.

The 1/f noise for a 1×1 mm^2 PbS photoconductor with the dark resistance of 300 kOhm is of the same order of magnitude as the noise in a commercially available metallic resistor, whereas for the PbS photoresistor of 5.5×6 mm^2 the 1/f noise is 5-6 times smaller than for a 1.8 MOhm resistance.

The laboratory setup used for the measurements is appropriate to accurately determine typical parameters of infrared detectors such as spectral responsivity, blackbody responsivity, specific detectivity, noise spectral density.

Acknowledgements

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