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A MICRO-BOLOMETER FOR FAR INFRARED (FIR) APPLICATIONS BASED ON BORON DOPED POLYCRYSTALLINE SILICONE LAYERS

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Abstract: Sources if noise in moderately doped (n_d = 10^{18} 10^{20} cm^{-3}, *r* = 0.002 – 1 Wcm) *p*–type (boron doped) poly Si resistors, used as a bolometer sensing element, at low frequencies are analysed. We demonstrate that the *1/f* noise in such resistors is well described by the Hooge relationship, and that parameter a_H is linearly proportional to the energy barrier height E_b. The noise generated in the contact areas of the *p*type resistors does not contribute significantly to the overall noise of the device. The test bolometer chip characteristics, developed at our laboratory specifically for evaluating the resistor film performance, closely follow the theoretical predictions of the accepted theory, making the design and fabrication of a usefull FIR detector possible.

Mikro bolometer namenjen uporabi v daljnem IR območju, zgrajen na osnovi tanke, polikristaline silicijeve plasti dopirane z borom

Kjučne besede: bolometer, tanke plasti, popirani polisilicij, šum, mikroelektronske tehnologije

Izvleček: V prispevku analiziramo izvore šuma pri nizkih frekvencah v zmerno dopiranem z borom (n_d = 10^{18} – 10^{20} cm^{-3}, *r* = 0.002 – 1 Wcm) polisilicijevem uporniku tipa *p*, ki je uporabljen kot seznorski element v bolometru. Pokažemo, da šum *1/f* v takšnih upornikih dobro opisuje Hoogeova enačba, da je parameter a_H v njej linearno odvisen od veliksto energijske bariere E_b med zrni polisilicija. Šum kontaktv upornikov tipa p ne prispeva znatno k skupnemu šumu celotne bolometrske naprave. Lastnosti testnega bolomotra na silicijevi tableti, ki smo ga v laboratoriju razvili posebej z namenom okarakterizirati lastnosti uporovne plasti, dobro opisuje veljavna teorija, kar nam omogoča načrtati in izdelati uporaben detektor za EM valovanja v daljnem IR območju.

1. Introduction

Due to the small photon energies photonic detector are unsuitable for detection of electromagnetic (EM) radiation with wavelengths longer than 12 ěm and therefore can not be used for detection of far infrared (FIR) and terahertz (0.1 to 10 THz, i.e. wavelengths between 10 ěm to several millimeters) waves. But in this range of the EM spectrum heat detectors are available, offering several advantages: their response is in principle not dependent on the wavelength of the incoming radiation, and are relatively simple to use and maintain as they do not require cooling to low temperatures, if temperature resolution of the order of ~0.1 K·Hz $^{-1/2}$ is sought. Such detectors have often been used for remote temperature measurements and in different motion sensors, however, advances in materials science and micromachining technologies have made fabrication of arrays of heat detectors possible that are used in thermo vision systems /1, 2/. All heat detectors absorb IR radiation and consequently their temperature rises. This temperature change is converted by the detector to a change of the output signal /2/ via a change of resistance of the device (e.g. in metal, semiconductor, or ferroelectric bolometers), a change in thermo-voltage, pressure (e.g. Golay cell), pyroelectric effect, etc. In this paper we present a study of the sensing materials for a bolometric type of heat detector, together with an example of the detector.

2. Bolometer parameters

The bolometric principle and several devices based on it have been studied in detail /3, 4/. The basic parameter of a bolometric device is its sensitivity (*S*). It is a function of the temperature coefficient TC of the device, its heat conductivity *G*, heat capacity *C*, and the time constant *ô* = *C*/*G*. Under the influence of the incident EM radiation of frequency *ů* and intensity P_o, the sensitivity of the bolometer is given by

$$S = \frac{V_s}{P_0} \approx \frac{TC \cdot V_d}{G\left(1+(\omega\tau)^2\right)^{1/2}} \qquad (1)$$

For a large response of the device to the incident EM radiation thus a material with as large as possible *TC*, and as low as possible heat conductivity *G* is needed. These may be conflicting requirements as the TC is determined by the materials used, and G, on the other hand, is basically determined by the fabrication technology employed. Its value can be lowered if the sensing element of the device is positioned in vacuum, whereby the heat losses are minimized. From (1) it would appear that the sensitivity could be conveniently increased by increasing the voltage drop V_s over the bolometer sensor, however, the signal voltage to noise voltage ratio of the bolometer must be also be considered.

Generally, there are three sources of voltage noise present in all types of resistors: the Johnson noise V_J , caused by the thermal motion of the charges in the sensing element, noise due to temperature fluctuations (the so called phonon noise), and the 1/*f* noise, due to recombination – generation effects in semiconductors and/or effects on grain boundaries /5/. The first two types of noise are frequency independent (white noise) and also independent of the current through the resistor, but not the 1/*f* noise. At low frequencies or/and high applied currents the 1/*f* noise becomes predominant. The Johnson noise is a white noise with a constant spectral distribution *S* over the entire frequency range. It is described by the well known equation

$$S_j = 4kTR \tag{2}$$

where *k* is the Boltzmann constant, 1.38 10^{-23} J/K. The spectral density of phonon noise is given /1/ by the equation

$$S_T^{1/2} = I(TC)\cdot R.\sqrt{\frac{kT^2}{G}} \tag{3}$$

and is linear with respect to the current through the bolometer structure. If the heat conductance *G* of the device is sufficiently small (below 0.1 mW/K), the phonon noise of the device approaches the Johnson noise. A much more serious source of noise in bolometers is the 1/*f* noise as the devices usually operate at frequencies of several 10 Hz and a relatively high voltage over the device. This contribution to the noise is described by the Hooge semi-empirical equation

$$\frac{S_H}{V^2} = \alpha_H \frac{1}{f\cdot N} \tag{4}$$

where $\acute{a}_H$ is the Hooge constant, *f* the frequency and *N* the number of charge carriers. The total noise spectral density (energy) is the sum of all 3 contributions,

$$S_n = S_j + S_T + S_H \tag{5}$$

The measured noise V_n is therefore the integral of spectral density S_n over the frequency range of interest

3. Experimental: polycrystalline silicone film properties

In designing a bolometric device with a polycrystalline silicon (poly Si) resistor the properties of the resistor film should be understood in extensive detail. Poly Si has been used in semiconductor manufacturing for decades as material for transistor gates, resistors, capacitors, etc. Due to its well established technology, and its electrical and mechanical properties it is also a very attractive material for a wide range of micro–machined devices and sensors. Unfortunately, there is a serious draw back in poly Si properties, if used in a bolometric device: its *1/f* noise /6, 7/ is large. Excessive *1/f* noise can seriously degrade sensor properties, especially in case of bolometers, where heating and sensing are combined in the same material. For instance, detectivity of bolometers fabricated on *n*-doped poly Si, as reported in /8, 9/, was by an order of magnitude lower than expected.

Poly Si films in this study were deposited on the top of an oxidized (50 nm) 100 mm Si wafers. The poly Si deposition was performed in a commercial LPCVD reactor by the decomposition of SiH_4 at the standard conditions, T = 625°C, p = 350 mtorr. Doping of 0.38 mm and 1.0 mm thick films was performed by ion implantation of boron (D_{ii} = $3\cdot10^{14}$ – $5\cdot10^{15}$ cm^{-2}, E = 40 keV). After poly Si patterning (two resistors geometries: 375 · 75 mm^2, and 375 · 5 mm^2) wafers underwent process steps typical for the standard CMOS processing with 2 mm minimal geometry, including annealing at 920°C and a 1000°C reflow. The final step was alloying in the forming gas at 420°C. The noise measurements were performed according to the technique described in ref. /10/, using a low noise spectrum analyzer HP 3585A.

It is known that the energy barrier between small Si grains in the poly Si film is a function of dopant concentration. As a first approximation the dopant concentration n_d is proportional to the ratio of the dose to the poly Si film thickness. In Fig. 1 we demonstrate that the energy barrier (E_b) in boron doped (*p*type) poly Si is proportional to $n_d^{-0.59}$ while in phosphorous doped (*n*type) the E_b µ $n_d^{-0.85}$. According to ref. /8/ the power of the concentrations above the critical concentration, ~$5x10^{17}$ cm^{-3}, should be be-

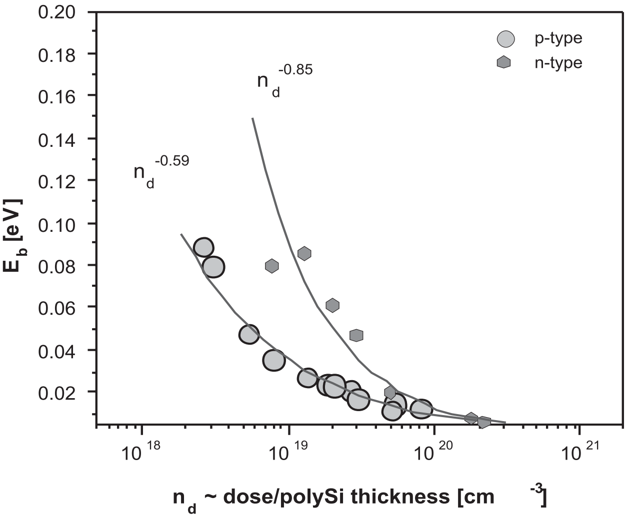

Fig. 1: FigEbConc:: Energy barrier height E_b *as a function of doping for* p– *and* n–*type poly Si. Concentration of dopant is defined as:* n_d *H” Dose/poly thickness.*

tween -0.85 and -1. Our measured values for the E_b of *p*-type correspond to the values given in /8/. On the other hand, the relationship between the resistivity *r* and the barrier E_b shows the same relationship for both types of poly Si.

The noise measured in a poly Si resistor, as described above, is the sum of the thermal and Johnson noise, *1/f* noise, and the noise of the measuring system. Spectral density $S_{1/f}$ of the noise is proportional to the square of the applied bias voltage or current I_o flowing trough the resistor. This relationship is demonstrated in Fig. 2, where the $S_V^{1/2}$ vs. I_o is plotted for convenience. For the particular resistor ($n_d \sim 3{\cdot}10^{18}$ cm^{-3}, *R* = 29.2 *kW, ?? f* = 75 Hz) the power of the current was 2.02, which is close to theoretical value /7/. This indicates that the noise is mainly generated in the depletion barrier region of poly Si. If the noise were generated in the grain bulk region the relationship would involve a higher power of I_o.

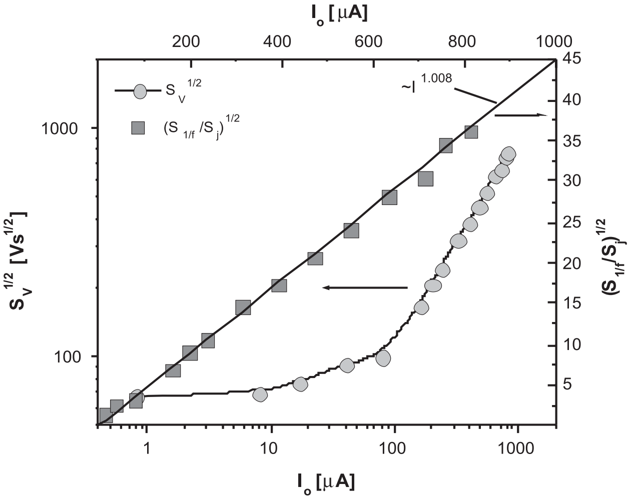

Fig. 2: Measured noise spectral density S$_V$ *and its* S$_{1/f}$ *component at* f *= 75 Hz as a function of the current flowing trough the resistor with* R *= 29.2 kW*

According to the theory the noise spectral density $S_{1/f}$ is inversely proportional to the frequency, $S_{1/f}$ µ f^{-1}. This is demonstrated in Fig. 3, where the frequency dependence of the same resistor as in Fig. 2 is plotted. The measured $S_{1/f}$ is proportional to $f^{-1.09}$, which is reasonably close to the theoretical value and published experimental data /10/: for *p*type resistors the reported values are -1 and -0.85 for *p* and *n*type poly Si respectively. Indeed, we have measured values about -0.9 for n-type poly Si bolometers /9/.

The dependence of the measured *1/f* noise on the current and frequency confirms the accepted notion that the noise is generated within the depletion barrier region of poly Si and not in the bulk of the grain. Data for thin 0.38 mm and thick 1 mm layers demonstrate that the noise is also independent of the geometry, and is influenced by the carrier number only. The main difference between the *p* and *n*type materials is the different energy barriers. Generally, the energy barrier in *n*type semiconductor is higher than in the *p*type for the same doping. And the same is valid for poly Si at low and medium doping levels (<10^{20} cm^{-3}), as indicated by our previous work /11/. Therefore the *1/f* noise is much more pronounced in *n*type material, unless the doping is so high that the segregation of the dopant on the grain boundaries occurs.

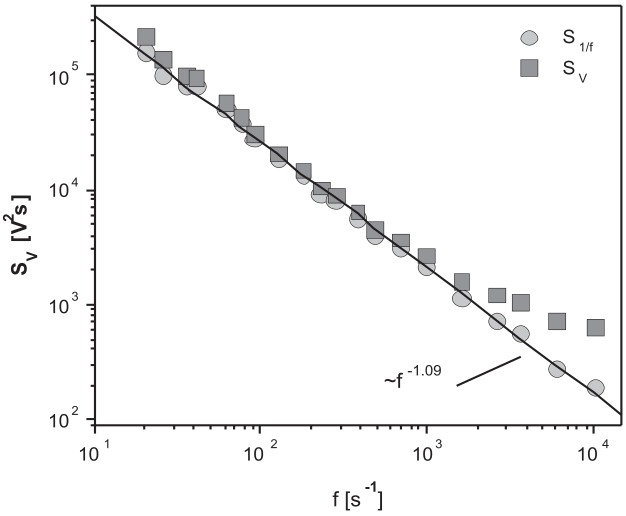

Fig. 3: Measured noise spectral density S$_V$ *and* S$_{1/f}$ *component as a function of the frequency for the same resistor as in Fig. at* I$_o$ *= 200 mA.*

For illustration, the specific resistively *ń* of the poly Si film as function of the dopant concentration is shown in Fig. 4.

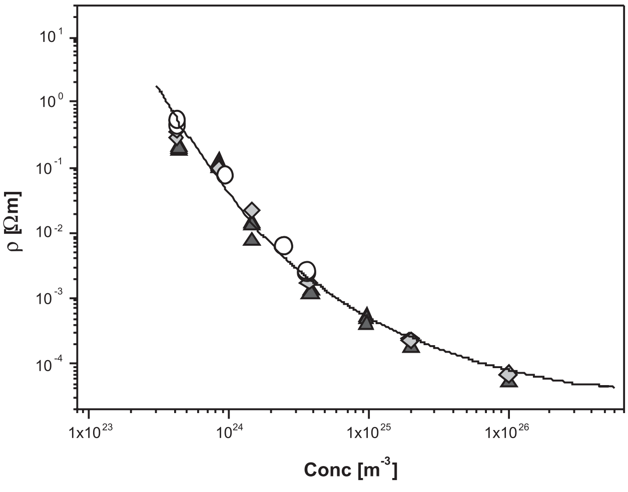

Fig. 4: The dependence of the specific resistivity of the poly Si layer on the the boron concentration, C = D$_{ii}$/deb$_{Si}$-C$_{out}$*. During the heat treatment, approximately* $6{\cdot}10^{23}$ m^3 *boron is lost. (% samples run # 1, f& sample run #2, % bolometer test chip, solid line - theory)*

For the bolometer applications significant Hooge parameter $á_H$, which controls the *1/f* noise of the poly Si, can now be conveniently presented as a function of the specific resistivity of the boron doped poly Si film (Fig. 5).

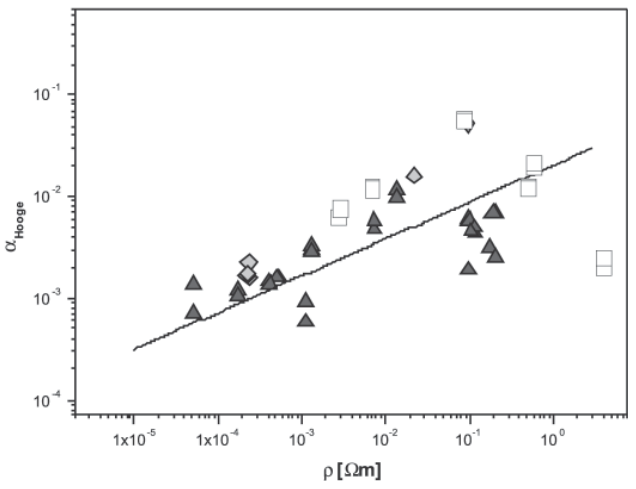

Fig. 5: The dependence of the Hooge parameter $á_H$ on the specific resistivity of the boron doped poly Si layer (% samples run # 1, f& sample run #2, % bolometer test chip, solid line – theory).

In step with the dopant concentration, the TC of the film is also changing with its specific resistance. The flow of the current through the film is associated with the tunneling of the charge carriers through the grain boundaries, where, *ń ~ exp(qE_b/kT)*, and E_b is the height of the barrier. In Fig. 6 the dependence of the TC, measured at 25 °C, is shown as a function of the specific resistivity of the boron doped polysilicon.

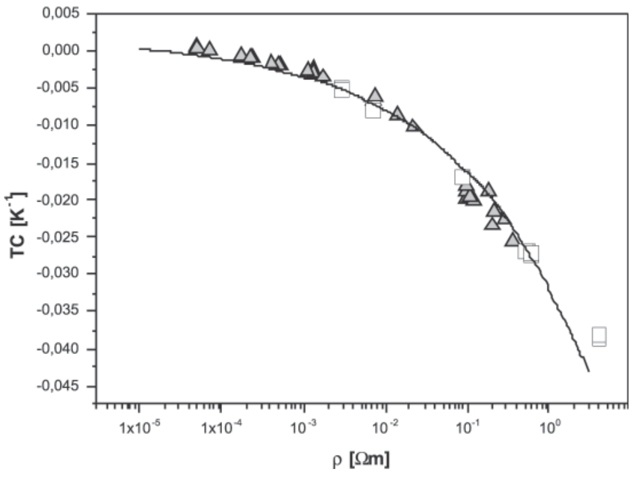

Fig. 6: The dependence of the TC *on the specific resistivity of the boron doped poly Si layer. (% samples run # 1 at 25 °C, % bolometer test chip, solid line – theory)*

Our measurements on contact chains indicate that the noise in the contact area to the *n*–type poly Si is extremely sensitive to the doping ($S_{1/f}$ µ n_d^{-4}) but not in the *p*–type ($\propto n_d^{-0.8}$). This indicates that medium and high resistivity *p*type resistors can be fabricated without additional doping of the contacts, contrary to the *n*type poly Si, where the contacts should be doped above $2 \cdot 10^{20}$ cm^{-3} which is typically done from a $POCl_3$ source.

4. Absorption of the EM radiation by the bolometer

An important consideration in evaluating a bolometer resistor performance is the absorption of the EM radiation by the active surface of the device. In the FIR domain a satisfactory absorptivity of the bolometer surface can be achieved by covering it with passivation films which are standard in the microelectronic fabrication technologies. Such an absorption film is formed by a LPCVD deposited PSG (refractive index n = 1.46) film, and a mixed SiON (n ~1.75) and SiN (n ~ 2) film, deposited by the PECVD method /12/. At longer incident radiation wavelengths a different approach is indicated, combining dielectric films with conducting films. The calculated absorption coefficients for PECVD SiON films of different thicknesses are shown in Fig. 7. Absorption at even higher wave lengths can be achived (up to 35 mm for PECVD a-Si with n=3.4) by increasing the index of refraction.

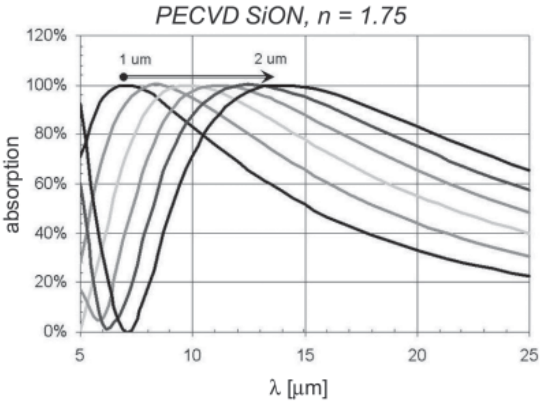

Fig. 7: The absorption of the bolometer surface as a function of the incident EM radiation wavelength at sheet resistance Z_o *= 377 Ů/ square for PECV SiON,* n *= 1.75, for 1 ěm to 2 ěm film thicknesses (in increments of 0.2 ěm).*

5. Bolometer fabrication

In the test bolometer fabrication, designed to analyze the poly Si films performance, special care was taken to consider only fabrication steps that are compatible with a standard CMOS technology with 2(3) layers of the poly Si. The fabricated test IC is shown on Fig. 8. The test chip enabled us to characterize the poly Si properties as described above.

6. Conclusion

Noise in moderately doped (n_d = $10^{18}10^{20}$ cm^{-3}, *r* = 0.002 – 1 Wcm) *p*–type (boron doped) poly Si resistors at low frequencies is dominated by *1/f* noise. Its spectral density $S_{1/f}$ is proportional to the square of the current flowing through the resistor, and we conclude that the *1/f* noise is generated within the depletion barrier region, not in the

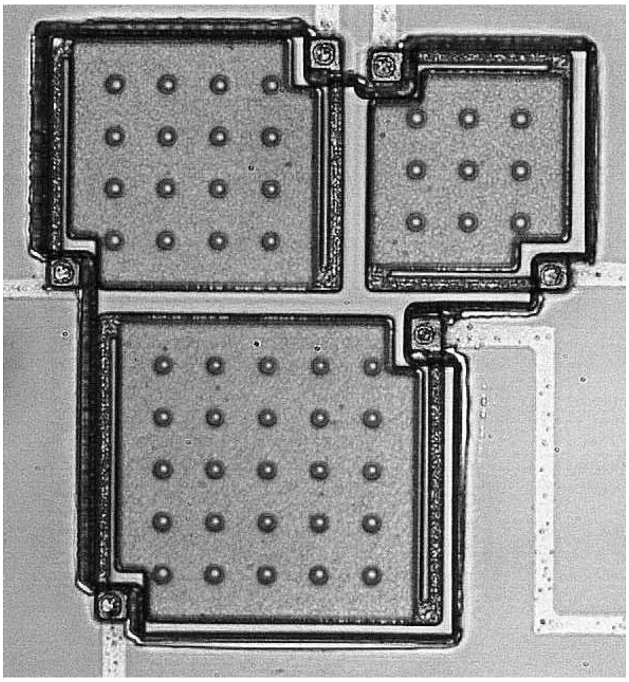

Fig. 8: The test bolometer device, comprising of three, 40·40, 50·50, and 70·70 ěm² bolometers. The resistor is supported by 2 ěm wide supports; the holes in the detector areas enable consistent under-etching of the structure during fabrication.

bulk of grains or in the contact areas. Spectral density $S_{1/f}$ is also inversely proportional to the frequency, and frequency dependent noise is well described by the Hooge relationship. Parameter a_H is linearly proportional to the energy barrier height E_b which itself is proportional to the doping, $E_b \mu n_d^{-0.59}$. Its values are from 10^{-2} to 310^{-3} for doping levels 10^{18} to 10^{20} cm^{-3}. Measured values for a_H are similar to the reported values for *p*–type boron doped poly SiGe /13/ and lower than reported for the *n*–type poly Si /7, 10/. The noise generated in the contact areas of *p*type resistors does not contribute significantly to the overall noise of the resistors. Therefore there is no need for additional doping of the contacts. The test bolometer chip characteristics, developed at our laboratory specifically for evaluating the resistor film performance, closely follow the theoretical predictions of the accepted theory, thus assuring us that the design and fabrication of a usefull FIR detector is within our reach.

7. Acknowledgement

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