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NOISE IN MEMS PIEZORESISTIVE CANTILEVER

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ABSTRACT

Though pezoresistive cantilevers are very popular for various reasons, they are prone to noise and they generate heat that can cause erratic beam deflection. The objective of this paper is to investigate electronic and thermal noise of a highly sensitive piezoresistive cantilever mainly used for Atomic Force Microscopy (AFM) applications. This work included the effect of temperature and impurity dependence of piezoresistance for modeling noise limited resolution. Doping thickness and density varied with both p and n type for measuring noises (Johnson and Hooge) and joule heating. Results are also applicable to other types of piezoresistive sensors.

Keywords:* *AFM, MEMS, Noise, Piezoresistive Cantilevers

I. INTRODUCTION

Micro/Nano-level sensor and actuators have emerged one of the most dynamic and exciting technologies since last two decades for their diverse and innovative applications. These sensors span a great variety of mechanical designs. With the invention of scanning tunneling microscope and development of the first atomic force microscope (AFM), various cantilever based sensors receive more and more attention for their small volume and high sensitivity. Simple cantilever beam type structures have been found to be especially suitable transducers of physical, chemical and biological stimuli into readily measured signals in forms of tip deflections and induced stress. The optical method for deflection read-out was developed for detecting cantilever deflection based on light beam reflection or laser light interferometry. However, the precise alignment and a large fraction of size limit its applications. To get rid of these problems, microcantilevers with piezoresistive element were introduced. A piezoresistive microcantilever has large dynamic range, CMOS integration facility and reliability. It can be used in any medium. Having detection mechanism inside the cantilever and easy implementation in large array allow them to compete with other types of cantilever such as piezoelectric, electrostatic, thermal etc. But piezoresistive cantilevers are prone to noise. Two major electronic noises are Johnson noise and 1/f noise. Johnson noise describes voltage fluctuations at the terminal of a conductor or semiconductor at equilibrium. These fluctuations are caused by the random vibrations of charge carriers in equilibrium with the lattice [1], [2]. Low Frequency noise is a frequency dependent non-equilibrium noise, which is predominant at lower frequencies. It is also known as 1/f noise. The mechanism that generates 1/f noise is still an active area of research. Two widely discussed mechanisms of 1/f noise are the fluctuation in the mobility described by Hooge [3] and the fluctuation in the number of carriers developed by McWhorter [4]. Piezoresistive cantilevers are vulnerable to thermal effects such as the variation in the temperature coefficient of resistance because of change in energy level of the carriers and the thermal deflection because of bimetallic effect. These effects change the characteristics of the piezoresistors significantly.

II. PREVIOUS WORK

Noise in MEMS sensors has been studied by many scientists who have focused on specific noise sources, which they believe limit their device performance [5-8]. Optimization analysis to improve sensitivity and reduce noise was also done [9-11]. Harley and Kenny [9] showed methods used for fabricating high-sensitivity piezoresistive cantilevers to improve their sensitivity, bandwidth, and noise. They discussed geometric and process parameter effects on cantilever sensitivity, bandwidth, and noise. Later [1], they gave a more detailed analysis for the optimization of piezoresistive cantilevers. In their work, sensitivity, noise, bandwidth, and spring constant were subjected to optimization based on cantilever geometry, process design, and voltage operation. They provided formulas and graphs showing the effect of thickness, length, and width on cantilever sensitivity. Thinner cantilevers yielded to an improvement of the sensitivity. Cantilever leg lengths were chosen judiciously since a trade-off between sensitivity and low frequency noise is involved through the number of carriers. For process optimization, shallow-doped cantilevers led to high noise, since the number of carriers was small. Deep-doped cantilevers led to low noise because of the large number of carriers. However, deep-doped cantilevers reduced the sensitivity since the sensitivity efficiency β derived by Tortonese [12] was smaller. There is therefore a trade-off between noise and sensitivity. The same effect is seen with the choice of doping concentration since the number of carriers plays a role in the noise and sensitivity readings. Harley and Kenny confirmed the presence of bulk 1/f noise in their cantilevers. They propose further studies on anneal to improve the quality of the crystal lattice in order to reduce the bulk 1/f noise. They also suggested that piezoresistive devices be biased according to their tolerance on power dissipation, to prevent either their destruction or the decrease of their performance, since at low frequencies the noise increases as the bias voltage squared.

This paper we introduced a highly sensitive piezoresistive cantilever and then investigated noises by taken care of piezoresistive properties.

Table 1: Table of variables

Var	Definition	Units
α	Hooge constant	-
β	Sensitivity efficiency	-
π_l	Piezoresistive coefficient	m^2 /N
ρ	Resistivity	Ω-cm
E	Modulus of elasticity	N/m^2
F	Force	N
F_{min}	Force resolution	N
f_{max}	Max frequency	Hz
f_{min}	Min frequency	Hz
k	Spring constant	N/m
k_B	Boltzmann's constant	J/K
l	Length	m

l_{leg}	Leg length	m
b	Width of leg	m
p	Doping density	cm^{-3}
q	Electron charge	C
Q	Joule heat	J
R	resistance	Ω
t	thickness	m
T	Temperature	K
t_d	Doped thickness	m
V_B	Bias voltage	V
V_j^2	Johnson noise power	V^2
V_h^2	Hooge noise power	V^2
w	Width	m
x	displacement	m
μ_p	Hole mobility	cm^2Vs^{-1}

III. PRESENT WORK

The objective of this paper is to design and analyze a new high sensitive piezoresistive cantilever design and characterize its noise with respect to atomic force microscopy application. For AFM, a concentrated load of 20 nN was applied to the free end of the cantilever. The proposed dual leg micro-cantilever (Fig-1) has a U-shaped piezoresistor (Fig-2) inside it. The design and analysis of the sensor is done using commercially available finite element analysis software. Single crystal silicon used as the base material of the cantilever. Both p+ and n- type doping of silicon used for piezoresistor. The noise depends on parameters like doping density, doping types, doping thickness, leg length, resistivity etc. In general the piezoresistive coefficient is a function of the impurity concentration and temperature. It is a decreasing function of concentration and temperature. Table-2 shows how longitudinal piezoresistance varies with doping density. This property is used for calculating noise and hence resolution. Comments on joule heating of the piezoresistor include both p and n type doping.

Table 2: Longitudinal piezoresistance factor as a function of doping concentration

Doping concentration (cm^{-3})	1×10^{18}	5×10^{18}	1×10^{19}	5×10^{19}	1×10^{20}
n-type (%)	98	92	85	52	34
p-type (%)	95	80	66	28	20

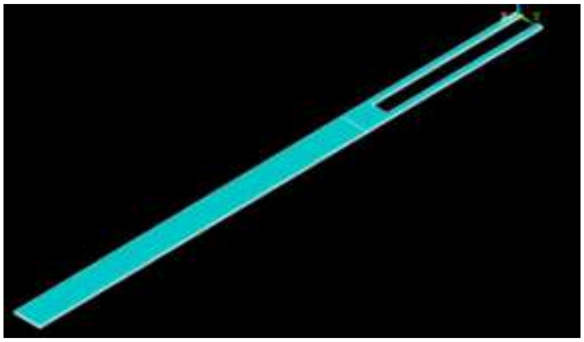

Figure 1: Dual leg microcantilever

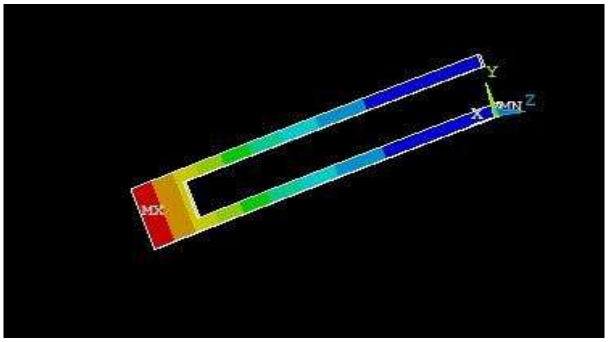

Figure 2: U-shaped piezoresistor (after applying force)

$$\frac{\Delta R}{R} = \frac{3\pi_l E t\left(l - \frac{l_{leg}}{2}\right)}{2\,l^3} x \tag{1}$$

$$V_j^2 = \frac{16 k_B T l_{leg}}{w t_d \mu_p q p} (f_{max} - f \tag{2}$$

$$V_h^2 = \frac{\alpha V_B^2}{l_{leg} w t_d p} \ln \frac{f_{max}}{f_{min}} \tag{3}$$

$$F_{min} = \frac{\sqrt{\left[\frac{\alpha V_B^2}{l_{leg} w t_d p} \ln \frac{f_{max}}{f_{min}} + \frac{16 k_B T l_{leg}}{w t_d \mu_p q p}(f_{max} - f_{min})\right]}}{\frac{3\pi_l V_B (l - l_{leg})}{4 w t^2}} \tag{4}$$

We know that,

$$R = \frac{\rho l}{A} \text{ and } Q = I^2 R T$$

So,

$$Q = \frac{V_B^2 T b t}{\rho(2 l_{leg} + w)} \tag{5}$$

Length of the piezoresistor has obtained by taking average of minimum and maximum length. All the legends have described in Table-1.

IV. RESULTS

Results show a significant increment of sensitivity (1) for proposed dual leg configuration (Table-3) than that of conventional one (approximately 2.15×). A higher quality factor cantilever withstands for Biosensors while a softer one shows prominent improvement of performances in AFM. Though piezoresistor length does not have significant effect on sensitivity in conventional micro-cantilever, a silicon cantilever shows inverse relationship between sensitivity and leg length illustrated in Fig-3. We varied cantilever length from 100 µm to 400 µm and piezoresistor length as 0.25l, 0.5l, 0.75l and l, where l is cantilever length. Width and thickness of the cantilever are 10µm and 1µm respectively.

Table 2: conventional Vs Proposed dual leg configuration

	Deflection (μm)	Surface Stress($\times10^{-6}$) N/m^2	ΔR/R ($\times10^{-3}$)
Conventional	0.374	0.95	0.686
Dual leg (Proposed)	0.737	2.05	1.48

In the frequency range from 10 Hz to 1 kHz, when Johnson noise (2) level is growing (Fig-6), Hooge Noise (3) has found to be decaying with larger leg length (Fig-8). Sensitivity and both types of noise are decreasing with increasing doping thickness.Fig-5,10,11 describe how noises, resolution, resistivity and piezocoefficient changes with respect to doping density. Johnson noise is found to be dominating for p-type doping than n-type. A comparison between Johnson noise and Hooge noise with respect to leg length has illustrated in the Fig-9. Minimum detectable force (MDF) (4) improved with increased doping densities (Fig-7) and doping thickness (Fig-4). It has also been found that Joule heating (5) affects more prominently for p+ type than that of n- type (Table-4). Bias voltage (V_B) kept 5V throughout this work.

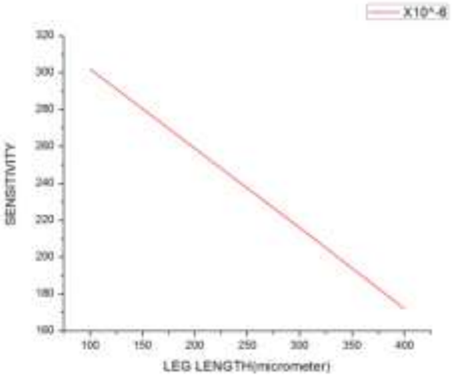

Figure 3: sensitivity with respect to cantilever length and leg length.

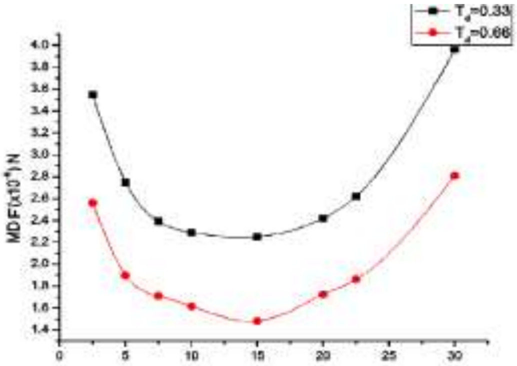

Figure 4: MDF with different doping thickness (T_d)

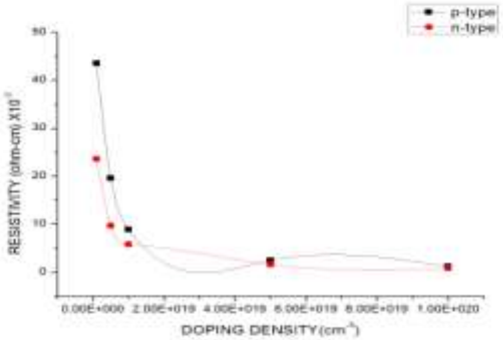

Figure 5: Variation of resistivity with respect to doping density

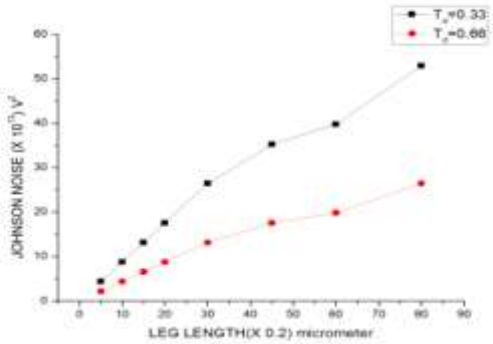

Figure 6: Johnson noise

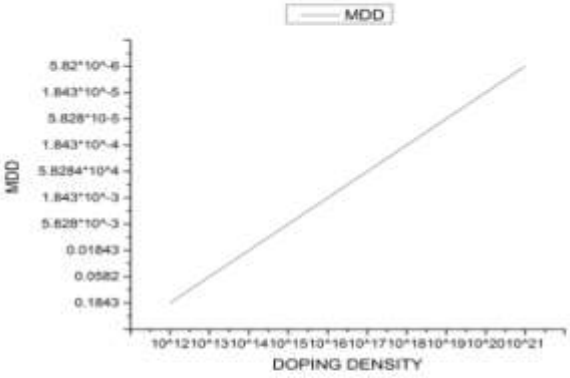

Figure 7: MDD Vs Doping density

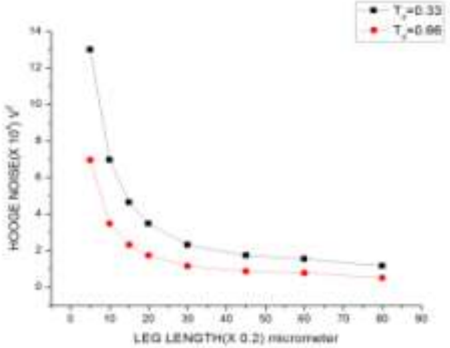

Figure 8: Hooge noise

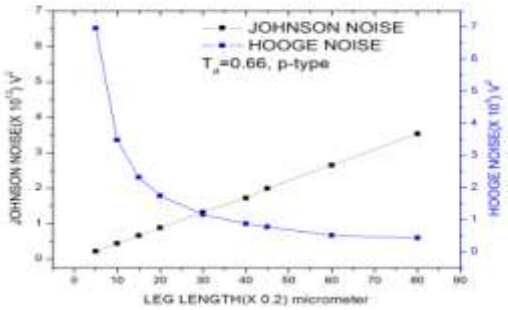

Figure 9: Comparison between noises with l_{leg}

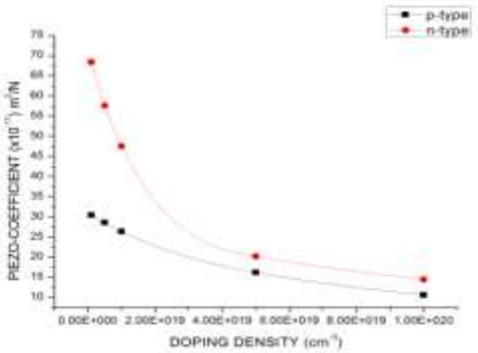

Figure 10: π_l with respect to doping density

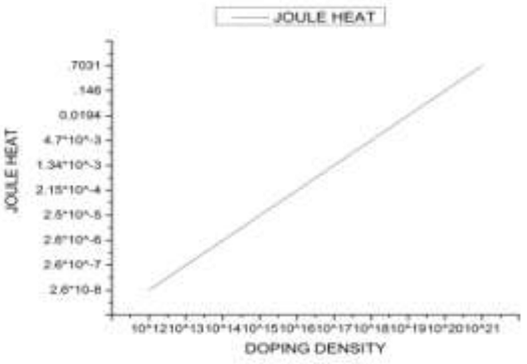

Figure 11:Joule heat with respect to doping density

Table-4: Joule Heat

Doping density cm^{-3}	**n-type (W)**	**p-type (W)**
10^12	2.6×10^{-8}	8.65×10^{-9}
10^13	2.6×10^{-7}	8.65×10^{-8}
10^14	2.6×10^{-6}	8.65×10^{-7}
10^15	2.5×10^{-5}	8.67×10^{-6}
10^16	2.15×10^{-4}	7.81×10^{-5}
10^17	1.34×10-3	5.56×10^{-4}
10^18	4.7×10^{-3}	2.58×10^{-3}
10^19	0.0194	0.0126
10^20	0.0146	0.096
10^21	0.7031	0.865

V. CONCLUSION

All the graphs and data were shown that validate sensitivity, noises and joule heating model in piezoresistive microcantilever. We found doping has a tremendous effect on performance of piezoresistive microsensors. Both n and p type doping has been varied along with different doping thickness and doping densities. It has shown that how geometry of the cantilever such as leg length affects sensitivity and both the noises (Johnson and Hooge). It is also included temperature and impurity effects of piezoresistor to calculate noises. Finally conclusion on noise limited resolution has been obtained. All the results shown in this paper are also applicable for other types of piezoresistive sensors.

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