Many current silicon piezoresistive cantilever designs use a single active element, and low impurity doping. This paper presents a design, which is optimized for low noise cantilevers, and suitable for static deflection measurements. The design is based on the authors’ experience, and experimental data from cantilevers of forty different implant-anneal conditions acquired over two years.

INTRODUCTION

The design of a silicon, piezoresistive cantilever is executed in an n-dimensional space of geometrical parameters such as length, width, thickness, crystallographic orientation and gage pattern, compositional and process parameters associated with dopant type, and concentration, materials employed such as silicon nitride, silicon oxide, and silicon, and performance metrics such as resonant frequency, sensitivity, repeatability, and thermal errors such as temperature coefficients of zero and sensitivity. Over the years, many designs have been presented which push this envelope in a given direction to achieve, for instance, small size and fast response. This work has a dual purpose. First, to implement lessons learned in a cantilever design which has four active piezoresistors in a temperature-compensated Wheatstone bridge, optimized for low noise and static measurements. Second, the design is intentionally positioned within the envelope of the aforementioned input-design parameters, so that it can serve as a reference design for subsequent work to optimize individual parameters.

EXPERIMENTAL

Forty wafers of DRIE-defined, SOI-etch-stopped, ion-implanted, piezoresistive, cantilevers beams were fabricated. Post-implant anneal temperatures ranging from 600 °C to 1050 °C, anneal times from 1 to 300 min were used as described in [1]. Two different beam thicknesses of 15 μm and 25 μm were fabricated. There were also short and long beam versions with beam geometries of 3.0 x 0.8 and 6.0 x 0.4 mm, respectively. Boron dopant concentrations ranged from 6 x10¹⁷ to 6 x 10¹⁹ cm⁻³.

There are many potential causes of noise in a silicon piezoresistive sensor, some better understood than others. The two dominant noise types are 1/f noise and Johnson noise. 1/f noise can be characterised by Hooge’s equation [2]:

\[ V_{ih} = V_b \sqrt{\frac{\alpha}{4N}} \]  

where \( V_b \) is the bias voltage applied across the piezoresistor in Volts, \( f \) is the frequency in Hz, \( N \) is the number of active charge carriers it contains, and \( V_{ih} \) is the voltage noise density in V/Hz⁰.⁵.

Empirically, 1/f noise has been described by \( \alpha \) which was found to be an increasing function of dopant concentration for a given piezoresistor geometry, anneal time and anneal temperature. For instance, we have plotted \( \log(\alpha) \) for a number of tested cantilevers as a function of anneal temperature (Figure 1).

Sensitivity measurement employed a laser-doppler vibrometer and resonance technique as described in [3]. Beam stiffness \( k \) was obtained by exciting the beam with vibrational white noise, measuring its first resonant peak, and using beam mechanics to determine each beam’s stiffness. Voltage output in a ¼ active Wheatstone bridge configuration was measured as a function of cantilever tip velocity while the cantilever was excited at resonance. Knowing the spring constant, the experimental sensitivity of the cantilever could be inferred from the following equation:

\[ \frac{V_e}{F} = \frac{3}{2} \frac{V_o \pi_i}{lw^3} \]  

where \( V_o \) and \( V_{ex} \) are the bridge output and excitation voltages in Volts; \( l, w \) and \( t \) are the beam length, width and thickness in meters, respectively. The piezoresistive coefficient \( \pi_i \) was obtained from the approximation given in [4] based on empirical data.

Figure 2 shows measured and calculated values of sensitivity for several cantilevers with two different beam thicknesses of 15 and 25 μm. The sensitivity decreases with increasing dopant concentration as predicted by Kanda [5].
PROPOSED DESIGN

The design shown in Figure 3 includes four piezoresistors in a fully active Wheatstone bridge for temperature compensation using passive thin film resistors or an active integrated circuit. Similar piezoresistor configurations are routinely employed in commercial pressure sensors and less often in cantilever beam sensors [6]. It is intended to provide for low noise and good static measurement stability. A lower resistance, deeper junction and higher impurity level of $10^{20}$ cm$^{-3}$, near solid solubility, significantly increases the number of carriers, thus improving low frequency noise and drift while only modestly decreasing $\pi$. Following the practice of commercial suppliers, an electrostatic shield [7] of polysilicon or metal [8] (which also acts as a photoshield) stabilizes mobile charges which could otherwise modulate sensor resistance. The advantages of high impurity levels for piezoresistors were recognized early in [9]. The comparison between the current and the new designs is shown in Table 1.

CONCLUSIONS

Based on measurements taken from sensors from a number of wafers processed with varying implant conditions, and with reference to the literature and commercial practice, we have presented the design of a temperature-compensated, piezoresistive cantilever sensor expected to exhibit low noise and good static stability.

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