

FORCE SENSING OPTIMIZATION AND APPLICATIONS

JOSEPH C. DOLL, SUNG-JIN PARK, ALI J. RASTEGAR, NAHID HARJEE,
JOSEPH R. MALLON JR., GINEL C. HILL, A. ALVIN BARLIAN, BETH L.
PRUITT*

Department of Mechanical Engineering, Stanford University, Stanford, CA, USA

Abstract Piezoresistance is commonly used in micro-electro-mechanical systems for transducing force, pressure and acceleration. Silicon piezoresistors can be fabricated using ion implantation, diffusion or epitaxy and are widely used for their low cost and electronic readout. However, the design of piezoresistive cantilevers is not a straightforward problem due to coupling between the design parameters, constraints, process conditions and performance. Here we discuss the equations and design principles for piezoresistive cantilevers, and present results from cantilevers and systems that we have developed for probing, mechanics studies and sensing, especially for low stiffness or large bandwidth applications.

1 Introduction

Piezoresistivity is a commonly used transduction mechanism in micro-electro-mechanical systems (MEMS) for transducing force [1, 2, 3], pressure [4, 5, 6] and acceleration [7]. The optimal sensor geometry depends upon the signal being transduced, but a simple cantilever beam is ideal for many applications. Microfabricated silicon cantilevers are widely used in force [8, 9], topography [10], and biochemical sensing [11] applications by transducing a signal via cantilever deflection. There are numerous techniques to detect cantilever bending, but the most common approaches are off-chip optical sensing [10] and on-chip electronic sensing using piezoresistive strain gauges [12]. Electronic sensing scales well to large arrays [13], high frequencies [14], and situations where optics are inconvenient [15]. Piezoresistive sensors in particular have several desirable characteristics such as straightforward fabrication, simple signal-conditioning circuitry, small size, and large dynamic range. With proper design, the resolution of piezoresistive cantilevers is comparable to optical detection [12, 2].

Here, we provide a brief review of the transduction principles which underly silicon piezoresistors, discuss some aspects of design modeling and optimization,

* Beth L. Pruitt, Stanford University, 496 Lomita Mall, Durand Building Room 217, Stanford, CA, USA e-mail: pruittb@stanford.edu

and describe several example applications from our lab. This is a survey and not a complete review of the extensive work on piezoresistors to date.

2 Modeling and Design

2.1 PRINCIPLES OF PIEZORESISTANCE

The electrical resistance (R) of a homogenous electrical conductor is a function of its dimensions and resistivity,

$$R = \frac{\rho l}{a} \quad (1)$$

where ρ is the resistivity, l is the length and a is the average cross-sectional area. The resistance of the conductor will change in response to the application of an external force based upon a change in (1) geometry and (2) resistivity. The response of doped semiconductor devices to loading is dominated by the stress induced change in resistivity,

$$\frac{\Delta\rho}{\rho} = \pi_l \sigma_l + \pi_t \sigma_t \quad (2)$$

where π_l and π_t are the longitudinal and transverse piezoresistive coefficients, while σ_l and σ_t are the longitudinal and transverse stress components where the piezoresistor is situated. A more thorough discussion of the history and mechanisms underlying piezoresistance in semiconductors can be found in [16].

The piezoresistive coefficients vary with dopant concentration. Experimental data was tabulated by Harley [17] for boron (p-type) piezoresistors. The longitudinal piezoresistive coefficient can be written as $\pi_l = P\pi_0$ where $\pi_0 = 72e - 11\text{Pa}^{-1}$ for a p-type piezoresistor oriented in the $\langle 110 \rangle$ direction and P is the concentration dependent piezoresistance factor, which is equal to

$$P = \log_{10} \left(\frac{b^a}{n} \right) \quad (3)$$

where $a = 0.2014$, $b = 1.53e22$, and n is the dopant concentration.

The piezoresistive coefficient varies according to the dopant type and the crystallographic orientation of the current flow relative to the applied stress. For a p-type dopant, the direction of maximum piezoresistive coefficient is the $\langle 110 \rangle$ direction, while for n-type dopants the optimum direction of stress and current is the $\langle 100 \rangle$ direction. The piezoresistance coefficients also depend on temperature [18], and the effect of temperature fluctuations on the output signal is commonly reduced by including an additional temperature compensation piezoresistor in the measurement circuit that is not subjected to a mechanical load.

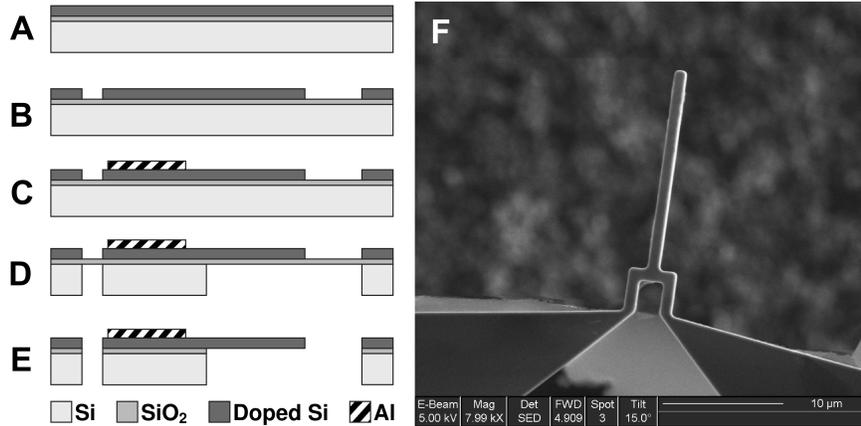


Fig. 1 Piezoresistive cantilevers are commonly fabricated using silicon-on-insulator wafers in combination with standard silicon micromachining processes. After the wafer is doped (a), the cantilever is defined (b) by reactive ion etching. Aluminum is sputtered to cover the frontside of the wafer and etched back to form bondpads (c). The cantilever is released by deep reactive ion etching from the backside of the wafer (d) followed by reactive ion etching of the buried oxide (e). A forming gas anneal is necessary to form low noise, ohmic contacts. An SEM of a finished device is shown in (f). Reprinted from Doll et al. [19]. ©2009 IEEE.

2.2 FORCE AND DISPLACEMENT SENSITIVITY OF A CANTILEVER BEAM

This model of piezoresistance is applicable to any piezoresistive device. In this section we specifically investigate the sensitivity of a cantilever beam, which is well suited for force detection.

We assume a split-leg cantilever design; two separate legs each of length l_{pr} and width $w_{pr} = w/2$ form a loop to define the piezoresistor. The cantilever extends beyond the end of the piezoresistor to a total length l . The thickness, t , is uniform along the length. The gap between the legs is assumed to be negligibly wide, and the cantilever can be approximated to have a uniform width w . The dimensions and one of many possible microfabrication processes to form a cantilever are illustrated in Figure 1.

The system is modeled as a linear elastic cantilever beam with a point load applied at the tip via Euler-Bernoulli beam theory. We assume negligible transverse stress in the cantilever legs, and the longitudinal stress induced as a function of distance x from the base and z from the neutral axis of the cantilever is:

$$\sigma = \frac{12F(l-x)z}{wt^3}. \quad (4)$$

The longitudinal stress induced by a point load is zero at the neutral axis, and varies linearly through the cantilever thickness, thus the stress experienced by the piezoresistor varies by position.

If the piezoresistor is uniformly doped, infinitely thin, and located at the surface of the cantilever where the stress is maximized, the fractional change in resistance is

$$\frac{\Delta R}{R} = \frac{6\pi_0(l - l_{pr}/2)}{wt^2} F \quad (5)$$

as derived previously [20]. In practice, these assumptions overpredict cantilever sensitivity due to the finite thickness of the piezoresistor. Therefore, we introduce an efficiency factor, β^* as in [21], which accounts for the finite thickness of the piezoresistor (Figure 1) and proportionally reduces the fractional change in resistance,

$$\beta^* = \frac{2 \int_{-t/2}^{t/2} q\mu n P z dz}{t \int_{-t/2}^{t/2} q\mu n dz} \quad (6)$$

where the majority carrier mobility, μ , and piezoresistive coefficient, P , are both functions of dopant concentration, n , which varies with depth, z . In the case of a uniformly doped piezoresistor with finite thickness t_{pr} , β^* simplifies to

$$\beta^* = P \left(1 - \frac{t_{pr}}{t}\right). \quad (7)$$

A simplified form of β^* was first derived in [12] before being extended to a dopant profile with varying concentration in [21]. The effects of post-ion implantation annealing on β^* is discussed in more detail in [22]. Briefly, β^* does not vary monotonically with anneal time because of the competing effects of dopant activation and diffusion.

A Wheatstone bridge is commonly used to transduce the change in resistance to a voltage. Although a bridge reduces the sensitivity of the system ($V_{out}/V_{bridge} \approx \Delta R/4R$), it is straightforward to implement. For the sensitivity and noise calculations, here we assume a quarter-active Wheatstone bridge with an additional temperature compensation piezoresistor.

The overall voltage sensitivity is given as

$$S_F = \frac{\Delta V}{F} = \frac{3\pi_0(l - l_{pr}/2)}{2wt^2} V_{bridge} \beta^* \gamma \quad (8)$$

where γ is the ratio of the piezoresistor resistance to the total resistance measured. Resistance that does not contribute to the change in resistance with applied force, such as contact resistance and conducting traces, acts to reduce system sensitivity and increase noise.

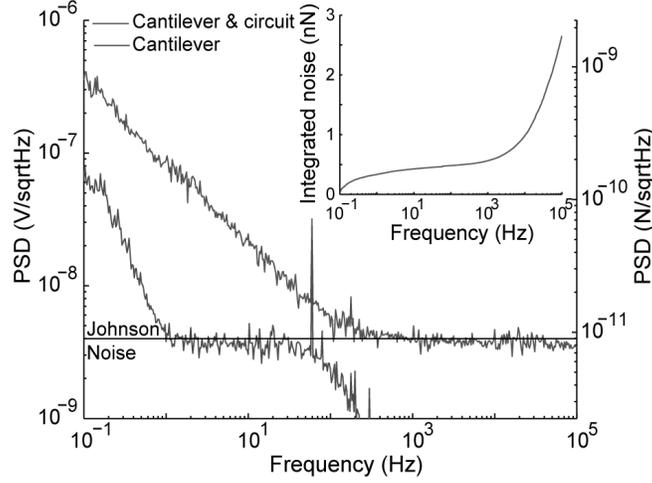


Fig. 2 Noise power spectral density (PSD) for a cantilever and associated conditioning circuitry, which illustrates the contributions of Johnson and low frequency noise from various sources. Inset: integrated noise from 0.1 Hz. Reprinted from Park et al. [23]. ©2009 IEEE.

2.3 NOISE IN PIEZORESISTORS

Piezoresistive cantilever performance is limited by two primary sources of noise: Johnson and 1/f (Hooge) noise [2, 1]. The noise inherent to signal conditioning circuitry must be considered as well and sets a noise floor for the piezoresistor.

Johnson noise is the result of the thermal motion of carriers within resistive elements and is independent of frequency [24]. The Johnson noise of a balanced Wheatstone bridge is equal to the Johnson noise of a single resistor, so that the integrated Johnson noise power of the Wheatstone bridge in the frequency band f_{min} to f_{max} is

$$\overline{V_J^2} = 4k_bTR(f_{max} - f_{min}). \quad (9)$$

The piezoresistor resistance (R) can be calculated from the dopant concentration profile and corresponding sheet resistance. Variation in carrier mobility with concentration should be considered [25]. For a sheet resistance of R_s , $R \approx 2R_s l_{pr}/w_{pr}$.

The primary 1/f noise source in silicon piezoresistors is Hooge noise [2]. The voltage power spectral density of a single piezoresistor has been empirically modeled as

$$\overline{S_H^2} = \frac{\alpha V_{bias}^2}{Nf} \quad (10)$$

where $V_{bias} = V_{bridge}/2$ is the piezoresistor bias voltage, N is the total number of carriers in the resistor, and f is the frequency. The parameter α is an experimentally

measured value that is believed to be dependent upon crystal lattice quality. Ion implantation causes damage to the crystal that must be annealed out, and it has been observed that α decreases with the mean diffusion length (\sqrt{Dt}) of the dopant atoms during the anneal. For epitaxial piezoresistors, $\alpha = 10^{-5}$ is typical [17] although values of α as low as 10^{-7} have been reported for implanted piezoresistors [26].

The Wheatstone bridge is composed of two piezoresistors which have uncorrelated $1/f$ noise sources so the $1/f$ noise power is increased by a factor of two, and the integrated voltage noise power is

$$\overline{V_H^2} = \frac{\alpha V_{bridge}^2}{2N} \ln\left(\frac{f_{max}}{f_{min}}\right). \quad (11)$$

The number of carriers can be calculated from the dopant concentration profile and piezoresistor volume assuming a constant current density [17]. For a piezoresistor with N_z carriers per unit area, $N \approx 2l_{pr}w_{pr}N_z$.

2.4 FORCE RESOLUTION AND DESIGN TRADEOFFS

The minimum resolvable force can be calculated from the root mean square voltage noise and the force sensitivity of the device according to

$$F_{min} = \frac{V_{noise}}{S_F} = \frac{\sqrt{\frac{\alpha V_{bridge}^2}{4l_{pr}w_{pr}N_z} \ln\left(\frac{f_{max}}{f_{min}}\right) + 8k_B T R_s \frac{l_{pr}}{w_{pr}} (f_{max} - f_{min})}}{\frac{3(l-0.5l_{pr})\pi_0}{2wt^2} \gamma V_{bridge} \beta^*}. \quad (12)$$

Force resolution is affected by several factors: cantilever dimensions (l , w , t), piezoresistor dimensions (l_{pr} , w_{pr} , γ), fabrication process parameters (N_z , R_s , α , β^* , γ), and operating parameters (V_{bridge} , T , f_{min} , f_{max}). The integrated noise and force resolution of an example piezoresistive cantilever are shown in Figure 2.

Force resolution improves with power dissipation, which can be shown by dividing the numerator and denominator of (12) by V_{bridge} to obtain

$$F_{min} = \frac{\sqrt{\frac{\alpha}{4l_{pr}w_{pr}N_z} \ln\left(\frac{f_{max}}{f_{min}}\right) + k_B T \frac{1}{W} (f_{max} - f_{min})}}{\frac{3(l-0.5l_{pr})\pi_0}{2wt^2} \gamma \beta^*}, \quad (13)$$

where W is power dissipated in the piezoresistor ($V_{bridge}^2/4R$).

It is clear that force resolution can be improved by increasing W to the point where Johnson noise is negligible. However, there is a limit to the maximum power dissipation sustainable by the cantilever because Joule heating can destroy the piezoresistor and large bias voltages lead to large leakage currents.

The piezoresistor length ratio and performance can be calculated for a variety of process conditions in order to find the optimal design, as in [27]. A notable result from our optimization work is that the integrated Johnson and $1/f$ noise should be

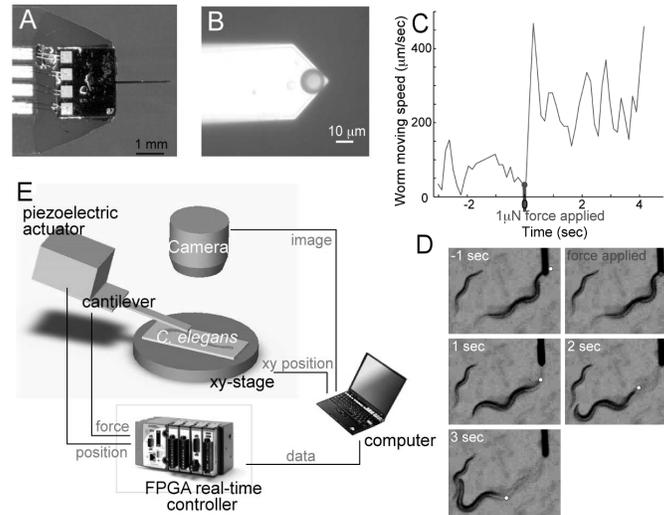


Fig. 3 Piezoresistive microcantilever (2 mm long, 30 μm wide, 7 μm thick) glued on printed circuit board (a) with a 10 μm diameter glass bead on the tip to provide a controlled contact geometry (b). A 1 μN force applied to *C. elegans* induces a change in velocity (c), measured using a behavior tracking and force application system (d). A schematic of the force and displacement clamp system using proportional-integral-derivative (PID) field programmable gate array (FPGA) controller is also shown (e). Reprinted from Park et al. [23]. ©2009 IEEE.

comparable ($\overline{V}_J \approx \overline{V}_H$) for typical design conditions and constraints. Alternatively, the optimized design can be found numerically as in [28], which provides a convenient interface for the designer and can handle arbitrary nonlinear constraints.

3 Applications

3.1 FORCE SENSORS

Piezoresistive cantilevers are well-suited for the study of biomechanics at the microscale; they cover the relevant range of forces (nN to 100 μN), displacements (nm to 10 μm), and offer sufficient bandwidth (10s to 100s of kHz). We used piezoresistive cantilevers to investigate two fundamental issues related to touch sensation in the nematode *C. elegans*: body mechanics [9] and the behavioral touch threshold [23]. *C. elegans* is a model organism for genetics studies, including the study of mechanotransduction, the conversion of mechanical energy into biomechanical signals.

In the first study, we used a piezoresistive cantilever to apply microscale forces to the nematode and develop a model for the mechanical structure of the body wall (Figure 3). In the behavioral study, piezoresistive cantilevers were used to measure

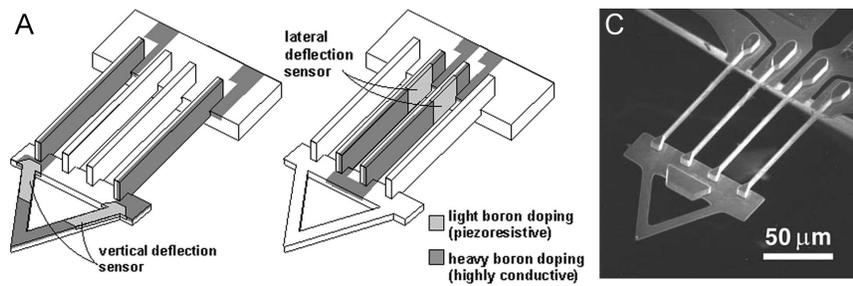


Fig. 4 (A) Dual-axis piezoresistive AFM cantilever with orthogonal axes of compliance. Oblique ion implants are used to form electrical elements on vertical sidewalls and horizontal surfaces simultaneously. (B) SEM image of a fabricated device. Reprinted with permission from Chui et al. [29]. ©1998 American Institute of Physics.

the minimum force detectable by wild-type *C. elegans* (Figure 3). By integrating the cantilever with a fast real-time controller, we developed a MEMS force-clamp system for applying user-defined force profiles (e.g. step, sinusoidal) to *C. elegans*. Using the system, we measured a touch sensation threshold ten times smaller than accessible with previous tools. Details of cantilever design parameters are presented in [22] and [27].

Piezoresistive cantilevers are particularly well suited for high frequency force sensing. The cantilever dimensions are limited only by fabrication constraints and force resolution continuously improves as dimensions are reduced. We fabricated 340 nm thick piezoresistive cantilevers doped by POCl_3 diffusion, yielding sub-nN force resolution with a measurement bandwidth up to 100 kHz [19].

Piezoresistors have been used to sense lateral or 'in-plane' forces in a micro-accelerometer [30] and underwater shear stress sensor [31]. Lateral piezoresistive sensors can be fabricated with ion implantation or epitaxy [32] and are typically located on vertical sidewalls in devices. Simultaneous sensing of two components of force has been demonstrated in cantilevers that combine sidewall piezoresistors with those oriented on a more usual top surface (Figure 4) [29]. Such dual-axis force sensors have been employed in data-writing applications and biomechanics studies of complex adhesion mechanisms [33].

3.2 SCANNING PROBE MICROSCOPY

Atomic force microscopy (AFM) with piezoresistive cantilevers was first demonstrated by Tortonese et al. [12]. Measurement of tip deflection via piezoresistive transduction has two advantages over the conventional laser beam bounce technique. First, the system setup is compact and inexpensive, enabling applications in space-constrained environments (for example, on upright or inverted microscopes or in cryostats). Second, because piezoresistive cantilevers do not require a laser,

samples are not susceptible to optical excitation, an important consideration in techniques such as scanning gate microscopy (SGM) [34].

In AFM, we are interested in optimizing the minimum resolvable tip displacement, d_{min} . Dividing (12) by k , the spring constant of the cantilever, we obtain an expression for d_{min} . By increasing k , we can improve the displacement resolution. Many scanning probe techniques are performed at liquid He temperatures (4.2K and below). Noise is greatly reduced for piezoresistive cantilevers operated in these conditions. Instead, power dissipation becomes a key design parameter as the cooling power of most dilution refrigerators is in the order of tens of microwatts.

With the considerations above, we have fabricated piezoresistive cantilevers with integrated coaxial tips. The probes can image nanometer topography in a 10 kHz bandwidth and the tips can generate tightly-confined electric field perturbations for high-resolution SGM.

3.3 CHEMICAL SENSORS

A functional chemical layer deposited on the surface of a cantilever can be used for chemical sensing by surface stress change induced cantilever deflection [35]. Cantilevers have been used for detecting DNA [36], pH [37] and explosives [35].

Piezoresistive sensors are especially well suited to this task, because they are small, low power, have a relatively stable DC response, especially if temperature compensated [15]. Additionally, several cantilevers may be formed into an array. If each layer has varying response to chemical species, both the type and concentrations of the constituent chemical species present may be determined by factor analysis. Silicon cantilevers should be as short and as wide as possible take advantage of the transverse piezoresistive coefficient [38].

Slowly varying signals are difficult to measure with piezoresistors due to $1/f$ noise at low frequency. By fabricating relatively large cantilevers in [26] with a high dopant concentration and large number of carriers, we reduced the $1/f$ corner frequency to below 1 Hz. Four active piezoresistors were included at the base of the cantilever in a full-bridge Wheatstone bridge configuration, and an integrated force resolution of 100 pN was realized between 0.1 Hz and 100 Hz (Figure 5).

4 Conclusions

In summary, piezoresistive silicon transducers are widely used in MEMS for their simple fabrication, ease of integration and low-cost. Piezoresistive cantilevers can be readily fabricated at the micro and nanoscales for high performance force sensing. We have presented an overview of piezoresistive cantilever design and optimization and summarized several example applications. Cantilever design must balance

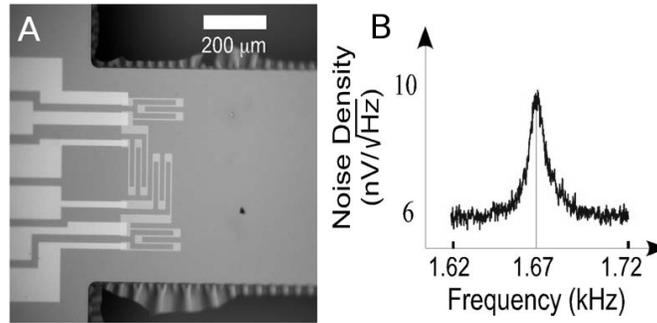


Fig. 5 (A) Silicon microcantilever, 3.5 mm long, 0.65 mm wide, and 15 μm thick with transverse and longitudinal piezoresistors. (B) Self-sensed thermomechanical noise spectral density for one of the fabricated cantilevers. Reprinted with permission from Mallon et al. [26]. ©2008 American Institute of Physics.

the competing requirements of low noise and high sensitivity in order to achieve optimized performance.

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