Sensors and Actuators A 269 (2018) 474–482

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Electrical contact resistance force sensing in SOI-DRIE MEMS

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ARTICLE INFO

Article history:
Received 31 August 2017
Received in revised form
14 November 2017
Accepted 5 December 2017
Available online 10 December 2017

Keywords:
Microelectromechanical systems
Microfabrication
Force sensing
Inertial sensing
Contact resistance

ABSTRACT

The use of electrical contact resistance (ECR) is investigated as a force sensing mechanism in silicon-on-insulator DRIE MEMS devices. Using both direct mechanical and indirect inertial loading, ECR relationships were evaluated for high aspect ratio silicon microstructures as a function of applied contact forces up to 45 mN. Forces applied *via* probe-induced spring elongation and accelerated proof mass allowed repeatable ECR-force relationships to be experimentally obtained. When normalized to initial contact resistance, chips subjected to inertial loading exhibited linearized sensitivities of 2.0%/mN and 2.1% hysteresis, with 1.6% relative standard deviation (RSD). Minimizing contact area during line contact loading was found to reduce RSD. However, line contacts loaded by manual spring elongation under a 5 mN pre-load and with radii less than 50 μm experienced upper sidewall fracture due to contact edge tapering from DRIE. In contrast, inertially loaded contacts with 25 mN of pre-load exhibited only corner surface fracture, indicating that higher and constant pre-load should produce more consistent contact conditions and better load distribution along the contact interface, subsequently reducing Hertzian contact pressure and preventing crack propagation. The presented design principles and experimental results reveal the ECR effect as a promising microscale force sensing mechanism for MEMS devices. The ease of fabrication, small size, and inherently rate-independent nature of ECR sensing offers an attractive approach to the measurement of large forces at the microscale, making this technique well suited for applications such as high-g inertial sensors.

1. Introduction

MEMS force sensors employ microfabricated elements to convert applied external forces to electrical signals, with transduction typically based on capacitive, piezoelectric, or piezoresistive mechanisms [1]. Capacitive force sensors are displacement-based sensors that are ubiquitous in MEMS applications [1–3], where a physical displacement between conductive elements resulting from an input force produces a change in capacitance that is converted into an output signal. In contrast, piezoresistive and piezoelectric force sensors are strain-based sensors, where strain within the material itself generates a change in resistance or charge, respectively, allowing these sensors to operate over large frequency and force ranges [4,5]. While these sensors have found commercial viability, the use of exotic or rate-sensitive materials with architectures that require complex fabrication limits application, particularly in scaled down or dynamic systems, resulting in relatively expensive devices.

In this paper, we explore an alternative force sensing principle in silicon-based MEMS devices that exploits changes in electrical contact resistance (ECR) during loading between two silicon surfaces. The change in electrical resistance is dictated by the number of contacting nano-asperities, which vary proportionally with elastic surface stress at the contact interface, and are therefore inherently rate insensitive. A key advantage of this sensing technique is that it does not require the use of selective doping, thin-film deposition, exotic materials, bonded structures, additional circuitry, or external transducers. Leveraging ECR as a force measurement technique presents the opportunity to create all-silicon microsystems capable of sensing applied force with minimal device and system complexity. Utilizing the ECR phenomenon as a sensing mechanism also offers the potential to realize integrated transducers with exceptionally high resonance frequencies. Avoiding the resonant effects seen in many existing sensors during high frequency loading [6,7], particularly in high-G environments where reliability of

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https://doi.org/10.1016/j.sna.2017.12.010

many MEMS devices is still unknown [8,9], may allow valuable enhancement of sensor bandwidth.

ECR as a sensing mechanism was first reported in non-destructive flaw detection [10], and later to measure strain in carbon fiber-reinforced concrete [11]. More recently, the ECR effect has been studied at the microscale using surface micromachined thin film polysilicon MEMS structures [12]. Although not explicitly investigated as a sensing mechanism, contact resistance between polysilicon surfaces was found to decrease with increased apparent contact pressure due to an increase in real contact area, with differing behaviors observed in loading and unloading conditions attributed to nanocontact asperities undergoing pile-up or sink-in, thereby affecting real contact area. Cyclic loading was found to produce erratic ECR behavior despite post-cycling surface imaging revealing only nanoscale surface polishing. As this was an investigation into using ECR as a non-destructive diagnostic tool, no characteristic behavior relating ECR and applied force was identified. ECR change in aligned carbon nanotubes (CNT) arrays has successfully detected small displacements in a 3-axis wide-band accelerometer, and experimentally verified to be highly sensitive compared to conventional piezoresistive sensors [13], while a CNT-based flexible strain sensor utilized resistance change between facing CNT bundles to detect strain [14]. In the robotics community, ECR-based tactile force sensors fabricated using screen-printed resistive layers have been investigated to simultaneously sense force and location of applied tactile forces [15]. Fabricated sensors were noted for their ability to be implemented without using adhesives for attachment.

For applications in MEMS-based sensing, high aspect ratio patterning of single crystal silicon by deep reactive-ion etching (DRIE) of silicon-on-insulator (SOI) wafers offers several important advantages over polysilicon surface micromachining, including the realization of larger masses, compliant structures with higher out-of-plane stiffness, and structures with nearly vertical sidewalls. To harness ECR as a sensing mechanism for DRIE structures, an improved understanding of the contact resistance of single crystal silicon surfaces processed by DRIE is needed. While DRIE has been widely employed for the fabrication of sensors utilizing capacitive or piezoresistive sensing, the ECR effect in contacting DRIE structures as a method to sense an external force has not yet been explored. To address this, here we investigate the sidewall contact resistance of high-aspect ratio silicon-silicon interfaces fabricated by SOI/DRIE as a function of contact force. Using two independent methods to apply force between the mating DRIE surfaces, namely direct mechanical probing and inertial loading, the impacts of loading constraints and contact interface geometries on the repeatability and sensitivity of ECR in DRIE microstructures are evaluated. Understanding the nature of the ECR mechanism in DRIE MEMS will enable the future development of novel microscale force sensors that may be realized using a simple and low-cost batch fabrication process.

2. Electrical contact resistance model

A general contact model for DRIE surfaces covered with a native oxide film is provided for current flow through micro-asperities at the contact interface. When two conductive surfaces are separated by a sufficiently thin insulating film, current flow can occur through quantum tunneling. Simmons [16] developed a set of tunneling equations to estimate the electrical tunneling resistance between two conducting surfaces with an insulating film barrier and generalized shape for all applied voltage levels. Greenwood and Williamson [17] developed a separate model to represent the contact interaction of two rough surfaces as the equivalent of one rough surface in contact with a smooth flat half-space with a reduced effective modulus. Identical insulating films atop the contacting surfaces can then be represented as a single film with thickness $t = t_1 + t_2$ (see Fig. 1). For very thin films ($t < 50$ Å), the contact mechanics of the film layers can be considered negligible compared to the underlying bulk material mechanical properties [18]. It is also assumed that surface interactions occurring at the contacting spherical asperities are sufficiently separated, thereby neglecting the asperity interactions as secondary [19].

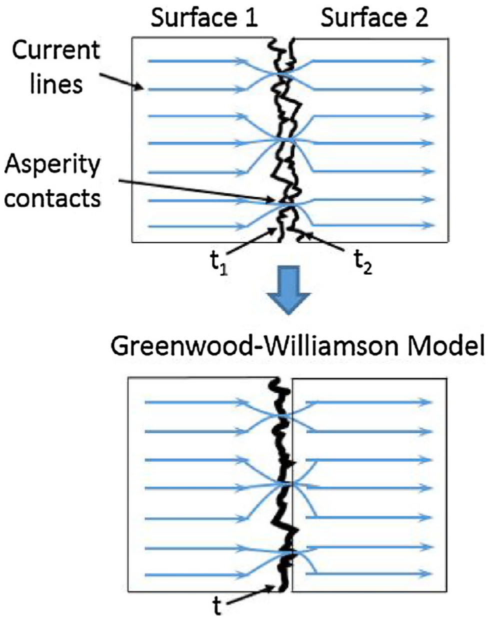

Fig. 1. Schematic of two contacting DRIE surfaces covered with insulating layers of thickness t_1 and t_2, and the equivalent Greenwood-Williamson model with a single insulating layer of thickness $t = t_1 + t_2$.

By combining the Simmons and Greenwood models, and representing rough surfaces with fractal geometry, [20] a general ECR model was created for conductive rough surfaces separated by a thin insulating film for elastic, elastic-plastic and fully plastic deformation of the micro-contacts over the full voltage range.

For conductive rough surfaces separated by a thin film, tunnel resistance is the only significant factor [21] in measurements where voltage ≤1 V and applied current is >10 μA [20]. Note that nearly all measurements in this work are taken at 1 mA with potentials less than 1 V. For wafers used in this work (boron doping concentration $n_A = 10^{18}$ atoms/cm^3) with thin film insulator thickness, t, <50 Å [16], the following equation gives ECR for a single microcontact in the low-voltage regime (within 1% error for $0.75\,\mathrm{V} < \varphi_0/e$) [20]:

$$R_i = \frac{\Delta S}{3.16 \times 10^{10} \varphi_L^{1/2} exp\left(-1.025 \Delta S \varphi_L^{1/2}\right) a_i} \qquad (1)$$

The above equation applies for determining the electrical contact resistance of a single microcontact with contact area a_i. Using an integration procedure [22], the total electrical resistance can be calculated over the full real contact area.

3. Experimental methods

Rather than employing miniature load cells or force sensing probes, *in situ* force methods were employed to characterize ECR-force relationships in fabricated devices. Many complex microsystems successfully utilize *in-situ* methods for actuation [23] and measurement within a microsystem [24,25], including with the aid of probe microscopy to measure mechanical properties