Contact resistance modeling for NEMS ohmic relays using highly doped SiGe contact material

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ABSTRACT

In an ohmic nano relay, the surface quality of the contact materials is crucial in determining the performance of the device and also its lifetime. An in depth analysis of the surface of an highly doped poly SiGe material, considered as a potential candidate for relay applications, is carried out. A new contact resistance model based on the contact surface characteristics, stiction in presence of moisture and wear susceptibility, are elaborated . Results indicate that highly doped SiGe contacts can lead to contact resistance of few tens of kOhm while reducing the wear probability. Due to large wettabililty, however, the device needs to operate in a sealed and dry environment.

Keywords: ohmic NEMS relay, SiGe, contact resistance, contact angle, hardness

1 INTRODUCTION

Recently, a large variety of NEMS components and systems have been investigated to enable new functionalities such as switches for use in non-volatile memories and logic[1,2]. In these kinds of devices, the ratio of surface area-to-volume is large and the adhesion forces become one of the dominant elements to achieve reliable mechanical performance [3]. Important performance criteria for ohmic NEMS switching devies are a low contact resistance and long lifetime, both of which are not easily achievable at the same time. Highly conductive soft metals generally deliver a low contact resistance but a poor device lifetime. The opposite occurs when harder contact material are used. Besdies low contact resistance, a good contact material should have enough hardness to have low erosion during cycling while low probability of stiction in presence of water. Some correlations have also been found to predict the device failure rate versus the roughness characteristics of the contact materials [4].

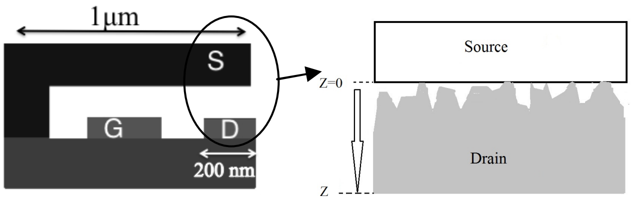
For ohmc contact switches, several studies on contact resistance have been presented [5-7]. Majority of the modeling work has been carried out with standard Gaussian distribution functions to model the surface roughness of the contact material. The surface of the contact is represented, according to the most used model elaborated by Greenwood [7], by a set of spherical asperities with identical end radius and different heights with statistical distributions. When the two surfaces come in to contact, first the highest asperities start to touch, next deform and current is conducted. Hence the real contact area is much smaller than the apparent one. With increasing the actuation force, the asperities will initially deform elastically before undergoing a plastic deformation when a critical force, determined by the hardness of the material, is applied. The accuracy of models that use statistical distributions of asperities to predict the contact resistance, become less accurate when used for nanoscaled contacts as the contact resistance becomes a strong function of the local asperity distribution.

The main aim of this work is to develop a model for the contact resistance of a NEMS relay using the real surface profile of the contacting material. All the elements of the device are made of chemical vapour deposited (CVD) poly-SiGe, a material with good mechanical properties and compatible with CMOS processing since the deposition temperature is below 450^{o}C [10]. The asperity distribution and height values were determined by AFM (Atomic Force Microscope) [8]. An estimation of the force applied on each asperity is obtained by using the hardness, the elastic modulus of the specific material and the contact area. The contact resistance is then obtained by using the deformation height and type (elastic/plastic), resistivity, contact radius and curvature end radius in the Hertz multi-asperities model [7,9]. Stiction in the presence of ambient moisture and contact wearability were also analyzed.

2 DEVICE STRUCTURE AND MATERIAL PROPERTIES MEASUREMENT

The NEMS relay used as a test vehicle in this work, consists of a 1µm long and 200nm wide cantilever as the source, which is suspended by a gap of 50nm on top of the a gate electrode for actuating the beam and a drain electrode to collect the current (Fig. 1a). The electrical contact area at the ON-state would be 200×200nm^2. The thickness of the cantilever, gate and the drain are 50nm, 200nm and 200nm respectively. The cross section depicted in Fig. 1b shows a magnification of the contact plane between the source and the drain. Along the Z axis, the movement of the contact plane between the two electrodes occurs. At Z=0 the force applied on the source electrode overcome the pull in voltage and the contact with the drain occurs. For positive Z values, higher force pushes the source deeper into the drain causing a deformation of the asperities that come in contact.

To measure the hardness, topography and contact angle of the drain electrode, a blanket layer of 400nm thick B-doped SiGe, with chemical concentration of 10^{21} at/cm^3,was deposited on top of a high density plasma oxide. Surface topography measurements were performed with AFM, which is the most commonly used technique to achieve quantitative data about surface roughness for nano-scale devices. The measurement resolution is sub-nanometer. Film resistivity was obtained from sheet resistance measured using a standard four points probe system obtained as average from measurement on 45 locations across a 200mm wafer.



(a) (b)

Fig. 1a Schematic representation of a the ohmic relay with source(S), gate(G) and drain(D), b) Schematic cross section along the Z axis of the source and drain contact plane (reference plane: Z=0).

Nano-indentation has been used to find the Young's modulus and hardness of materials using Continuous Stiffness Measurement(CSM) method[11]. A nano indenter with diamond tip was utilized to indent the sample to a depth of a few nm. Hardness is then defined as the ratio of the maximum load to the projected area. In comparison with gold, as shown in table 1, poly SiGe has higher hardness and Young's modulus and it is therefore expected to be more rigid. Hardness and Young's modulus can be in fact representative for the probability of wear in the material in contact [3]. Poly SiGe might lead however to higher contact resistance due to higher resistivity and oxidation when exposed to ambient as compared to gold.

The wear of the contact is an important reliability aspect in Ohmic relays and it refers to the damages induced during operation on the surfaces at the contact region [12]. Low hardness metals like gold, which shows a low contact resistance, are unlikely to be used for relays with long lifetime due to their low hardness and high probability of some effects like pitting, hardening and damaging after repeated cycling.

3 SURFACE ENERGY ESTIMATION

Besides the wear, stiction is also one of the determining factors which deteriorate the lifetime of ohmic relay. Stiction is intrinsically linked to the contact surface properties, number of asperities in contact and to the ambient in which the relay operates. Often it takes place either due to the presence of water and therefore capillary condensation at the contact region or due to the Van der Waals force between the contacting surfaces [4]. Contact angle (CA) has been used to evaluate the surface energy of the contact material. The CAs were measured using SEA 20 in the ambient conditions (22°C and the relative humidity 45%-55%). For a good estimation of the surface energy, it is necessary to measure the CAs of the material surface with water and diidomethane as a polar and non-polar liquid respectively. In the equations of Fowks [13], the adhesion energy is the sum of a polar and a non-polar dispersive component:

$$\gamma_L(1+\cos(\theta)) = 2[\sqrt{\gamma_L^d \gamma_S^d} + \sqrt{\gamma_L^p \gamma_S^p}] \qquad (1)$$

Where γ_S and γ_L represent the adhesive power of liquid and solid material respectively. Knowing the adhesion energy of the liquid and measuring the CA of two different liquids[14], one can calculate the adhesion parameters of the desired solid. Table I shows that the surface energy of a SiGe surface is larger than the one of a gold surface, implying that SiGe contacts are more prone to stiction as compared to gold contacts. For SiGe relays is therefore of key importance the ambient of operation and an hermetically sealed vacuum package.

Table 1 Material properties of SiGe and Au

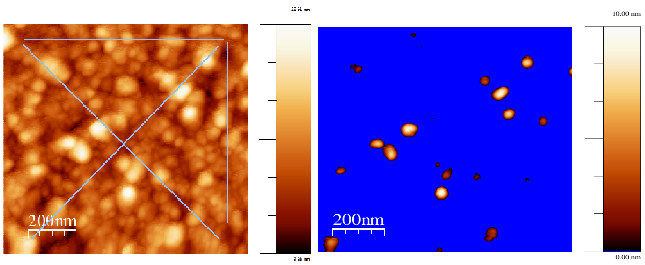
Material property	SiGe	Au
Elastic modulus (GPa)	115	58.5
Hardness(GPa)	9	1.47
Poisson's ratio[11]	0.28	0.44
Resistivity(nΩ.m)	9800	22
CA of DIW	5°	75°
CA of CH2I2	27°	25°
Surface energy(mJ\m^2)	145	91

4 CONTACT RESISTANCE MODELING

In this model, the surfaces are assumed to be clean and without any insulating layer at their interface and the roughness of both contacting surfaces were taken into account. Greenwood showed however that the two rough surfaces could be replaced simply by an equivalent rough surface in contact with a flat surface [5]. As the drain bottom electrode is planarized prior to the actuation gap oxide deposition, it is assumed that the bottom of the movable beam(source) which comes into contact with fixed bottom electrode(drain), is a smooth surface and the roughness is negligible in comparison to the drain electrode. AFM imaging resulted in RMS of 6nm for SiGe before and RMS of 0.5nm after planarization. We can therefore conclude that the bottom electrode is much rougher than the top contact surface.

For simplicity an average value was considered for the curvature radius of the asperities. Intercept method was applied to find an average asperity curvature radius from

AFM imaging of the surface. Horizontal, vertical and diagonal cross lines were used to find a more accurate average curvature radius. This radius is obtained by cutting the topography profile at specific lines, counting the number of peaks of the surface profile across that cutting line, dividing the length of the line by the number of peaks and then finally finding a grain curvature radius by averaging. Figure 2a shows an AFM image of the SiGe drain electrode surface while figure 2b visualize the number of asperities that would be in contact if the source electrode would be 10nm deep into the drain.



(a) (b)

Fig. 2 (a) 2D AFM image showing the surface roughness of SiGe($1\times1\mu m^2$) and crossing lines in vertical, horizontal, 135° diagonal, 45° diagonal (b) Contact spots found from AFM image at Z=10nm (see Figure 1 for definition of Z).

The number of asperities coming into contact is the fundamental information to input into the model. This value depends on the position of the contact plane between the source an the drain. Just after pull in, the contact plane is in position Z=0 and only one or few asperities are in contact. When the force increases, the contact plane moves along the Z axis to positive values and the number of asperities in contact increases. Once the number of asperities for each positive Z values is known for the total contacting area then the contact force can be predicted. The contact resistance of the relay can be calculated from the contact area and deformation type of the asperity in contact. The contact area of each asperity will be modeled with a circular spot shape with effective radius $r_{i,eff}$. For a given separation distance from the reference plane h and a known surface roughness distribution, the number of asperities in contact and their deformation can be determined from AFM image analysis (d1 = h,....,di). .

As indicated in Fig. 2(b), the brown region represents the real contact spots at Z=10nm. The total load bearing area is the sum of these brown spots. The equation of Hertz theory for elastic deformation [6] can be used to find the effective radius of the contact spot and then depending on the kind of deformation, the contact force of the corresponding spot for each asperity in contact can be calculated. In weak force region, there is large enough separation from the reference plane, thus the asperities can be assumed independent and the total force is the sum of the forces on all individual contact spots. In general this is equivalent of saying that the radius of contact area is small compared to the separation between the spots themselves.

If the contact area is considered to be a circle with radius of $r_{i,eff}$ then it can be obtained from $r_{i,eff}=(d_i\times R_{avg})^{0.5}$, [15] where R_{avg} represents the average of asperity peak radius of curvature and d_i is the vertical deformation of the asperity. The Hertz model [16] can be used to relate the vertical contact force at each surface asperity to the effective contact radius and average curvature radius:

$$F_{c,i} = r_{i,eff}^{3} \times E_{eff} \times R_{avg}^{-1} \tag{2}$$

Where $E_{eff} = [(1-\nu_1^2)/E_1+(1-\nu_2^2)/E_2]^{-1}$ and E_i and ν_i are the Young's modulus and Poisson's ratio for the two contacting surfaces. The total contact force is the sum of forces acting on each asperity in contact(Fig. 5).

This equation is valid only when the deformation is in elastic region and the deformation is reversible. As the contact force increases and hence the vertical deformation increases, the deformation of those asperities will become plastic at which the pressure at contact is independent of contact load and equal to the material hardness, H. In this model abrupt transition from elastic to plastic zone is considered for simplicity. The vertical deformation of the asperity at this transition point is given by [17]:

$$d_c = \left(\frac{\pi H}{E_{eff}}\right)^2 R_{avg} \tag{3}$$

Once the deformation of an asperity exceeds the above value, it starts to behave plastically. For high-conductive metals the critical deformation value is really small such that plastic deformation starts almost from the beginning of applying the load on the contacting surfaces. For instance for gold, with average curvature radius of 25nm, the critical deformation would be 0.22nm which is really close to zero and it indicates plastic kind of deformation for even weak loads.The critical deformation for SiGe is around 8nm. Fig. 4 illustrates the ratio of elastically deformed asperities to the total number of deformed asperities as a function of distance from the reference plane position. The force equations(eq. 7) shows that for the voltages around 35V, the distance from reference plane would be 7nm. So this figure shows that SiGe behaves elastically in typical operating voltages of the NEMS relay, which is one of the advantages of using this material in nano relays.

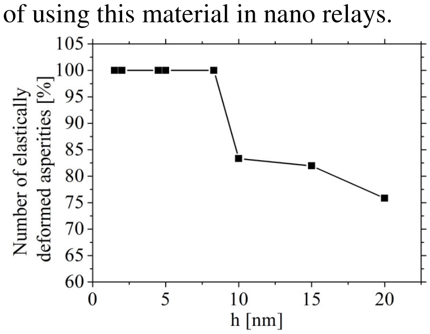


Fig. 4 Percentage of elastically deformed asperities versus the voltage difference between G and D

When the applied load to surfaces increases, one can simply consider an abrupt transition between elastic and plastic behavior of asperities such that it starts at certain value of deformation. In the fully plastic deformation region, the deformation persists and the contact pressure becomes equal to hardness and independent of contact force. In fully plastic deformation region, the vertical deformation d_i relation with contact radius is changed as follows:

$$r_{i,eff} = \sqrt{\left(2 - \frac{d_c}{d_i}\right) d_i \times R_{avg}} \tag{4}$$

If contact radius $r_{i,eff}$ is bigger than electron mean free path (l_e), Maxwellian spreading resistance model can be used in which electron transport through connections happens by electron diffusion[16]. Otherwise the Sharvin formula can be employed in which electrons are projected ballistically through the contact spots without scattering [18]. Majumder used the following equation to find the total resistance of contact:

$$R_{c,i} = \frac{4\rho l_e}{3\pi r_{i,eff}^2} + \upsilon\left(l_e / r_{i,eff}\right) \frac{\rho}{2 r_{i,eff}} \tag{5}$$

Where υ is varying from 0 to 1 as a function of l_e/r_{eff}[19]. In order to find a lower limit for the total contact resistance of a surface with varying contact area, one can consider the asperities as independent and conducting the current in parallel. To have an upper bound for the contact resistivity, one can consider the total surface in contact with a big circle of effective radius as defined as below[9]:

$$r_{t,eff} = \sqrt{\sum_i r_{i,eff}^2} \tag{6}$$

In this way, all of individual conducting spots are modeled with a single large effective circle and the total contact resistance is the result of this single contact spot.

If one needs to know the required voltage applied on the gate to reach this resistance, it can be easily calculated from replacing the total contact force in the total force equilibrium equation [20].

$$F_{elastic} = F_c + F_{electrostatic} \tag{7}$$

Since the surface roughness distribution is not always the same for a single contact material in the contact region of the relay, a kind of averaging over a bigger surface was used to have a better estimation of the smaller contact region of the relay. Fig. 5 shows the modeled contact resistance and contact force as a function of applied voltage at gate. It can be observed that at operating voltages around 12V the contact resistance start to saturate at values below 10KOhm and the device is still operating in an elastic regime as the contact force is still well below the voltage threshold that enable plastic deformation.

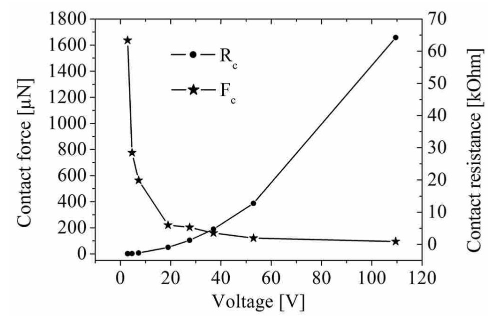


Fig. 5 The calculated contact resistance(R_c) and contact force(F_c) as a function of applied voltage on a gate for a 200×200nm^2 contact area

5 CONCLUSION

A novel method for contact resistance evaluation of contact surfaces in ohmic relayes was proposed. Since in NEMS devices the number of asperities in contact is limited so , the statistical distributions for asperities of the surfaces in contact is not applicable anymore. AFM imaging as a powerful technique was introduced to find a more real value for the contact resistance. In conclusion, highly doped SiGe contacts can be wear-resistant and allow contact resistances of a few tens of kΩ, but stiction can occur if the device is not operating in a sealed and dry environment

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