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Low frequency noise in the unstable contact region of Au-to-Au microcontact for microelectromechanical system switches

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The noise behavior of Au-to-Au microcontact for microelectromechanical system switches has been experimentally studied in the unstable contact region. The results suggest that the electrical conduction remains nonmetallic at the initial stage during contact formation due to the existence of alien films, and traps in the alien layer located at the contact interface could play an important role in determining the conduction noise. The conduction fluctuation induced by electron trapping-detrapping associated with the hydrocarbon layer is found to be an intrinsic noise source contributing to the low frequency noise in the unstable contact region. © *2014 AIP Publishing LLC*.
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Microelectromechanical system (MEMS) switches offer attractive alternatives in radar and communication systems, due to their advantages such as high isolation, low insertion loss, and high linearity.[1] Noise of MEMS switches has been drawing increasingly research interest, and coupling of electrical, mechanical, thermal, and other mechanisms raises a primary challenge in designing and modeling high performance RF MEMS devices.[2] The effects of Brownian, acceleration, acoustic, and power supply noise were investigated, which resulted in both amplitude and phase noises associated with MEMS devices.[3–5] However, the electrical conduction noise of ohmic-contact MEMS switches has not received much attention so far. On the other hand, the electrical contact instability under low contact force has been observed,[6–8] which could result in low frequency noise in MEMS devices. Scaling down of MEMS switches to sub-micrometer and nanometer region makes them more susceptible to unstable contact behaviors, due to the drastically reduced contact force.[9] In this paper, we investigate the low frequency noise of Au-to-Au microcontact of MEMS switches. Lorentzian and $1/f^2$ components are identified in the power spectral density (PSD) of the electrical conduction noise. The mechanisms of the noise components are further analyzed. The results show that the electrical contact instability is closely related to the alien film on the contact surface, and the trapping-detrapping process of electrons at the contact interface could be an intrinsic noise source in ohmic-contact MEMS/NEMS switches.

A devised nanoindentation platform was applied to perform the experiments in this work. The setup is built on an active optical table to isolate the testing system from external vibrations. A piezo-actuator is connected with PC workstation, which is able to produce smooth and continuous vertical motion within a range of a few nanometers repeatedly. The contact part uses a "ball-on-flat" configuration. The tip of the piezo-actuator is brought into contact with the sample placed on the X-Y stage during contact making; meanwhile, the changes in contact voltage versus loading time are captured by a digital storage oscilloscope, with a maximum sampling frequency of 100 MHz. Coaxial cables with BNC connectors are used for the connections to minimize the delay time and avoid any possible electrical interference. Similar systems could be found in the literature for contact tests.[7,8] Fine control of the ball position with the piezo-actuator allows the tests to be performed under low contact force with high accuracy and repeatability. The testing samples were prepared in a cleanroom following a typical process flow for RF MEMS switches using gold as the metal contacts.

High vacuum electron beam evaporation was used to coat gold film onto the ball tip of piezo-actuator and polished Si sample surface. A titanium film of 0.1 μm was deposited as an adhesive layer, followed by deposition of 1 μm gold film. The ball tip and sample were cleaned by the standard cleaning procedures in clean room before contact testing. Two groups of samples (group A and group B) were used in this study. Samples in group A were exposed in the MEMS fabrication environment for one complete lithography cycle before the contact tests, to mimic the surface condition of gold contact after microfabrication; while group B was used as a reference group, with samples tested immediately after preparation.

For some of the test samples, the contact surfaces were studied by using X-ray photoelectron spectroscopy (XPS). Alien films containing oxygen, nitrogen, and carbon species were found in both groups with different thicknesses, which could originate from absorption of air-born species such as hydrocarbons and carbon dioxide[10,11] or the process residues.[12,13] Thickness of the alien films for groups A and B was determined to be ~0.4 nm and 2 nm, respectively, by using XPS depth profiling. The samples from group A exhibit a thicker alien layer, which could be due to the contamination of photoresist residues in the lithography process.

A large number of contact tests were performed under precisely controlled operational conditions. The tip displacement velocity of the piezo-actuator was fixed at (10 ± 0.9)

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nm/s, and the applied contact voltage varied from 80 to 300 mV. Typical curves of contact voltage versus loading time for samples in groups A and B are shown in Fig. 1. The contact voltage V_c was measured between the gold coated ball tip of the piezo-actuator and the sample surface. The applied voltage was 95 mV. The fluctuation of contact voltage V_c was captured by the digital storage oscilloscope. The contact instability can be seen for both cases, before formation of stable electrical contact. The sample of group A with a thicker alien layer shows a remarkably longer unstable region as compared to the sample from group B.

It has been widely accepted that, when examining the electrical contact formation process between microcontacts, the hydrocarbon alien layer at the contact surface which physically separates the metal electrodes has to be taken into consideration.[7,12,13] Consequently, the contact may remain nonmetallic in the low force region, until the insulating alien film is eventually penetrated mechanically or broken down under electrical stress and heat. In the unstable region under low contact force, electrical conduction could be attributed to tunneling process through the alien films, and traps located at the contact interface may play an important role in determining the charge transport. Figure 2 shows a close-up on the transition period for a typical testing result from a sample in group A. The waveform is similar to a two level random telegraph signal (RTS) noise, which fluctuates between "on" and "off" states. The switching behavior can be explained by the charge trapping and detrapping processes.[6]

To better understand the physical origin behind the contact noise in low frequency region, the PSD of the contact voltage (V_c) fluctuations in the unstable region was obtained by conducting fast Fourier transform (FFT) for the time domain measurement results. Figure 3 shows the typical PSD as a function of frequency measured from samples in group A and group B. If the contact noise is due to the current tunneling and carrier trapping/detrapping in the insulating alien layer, the spectral noise density should be in the form of Lorentzian type.[14] At a single active trap energy level, which is evidenced by the two level RTS behavior in Fig. 2, the Lorentzian type spectrum associated with trapping and detrapping in dielectrics can be expressed as

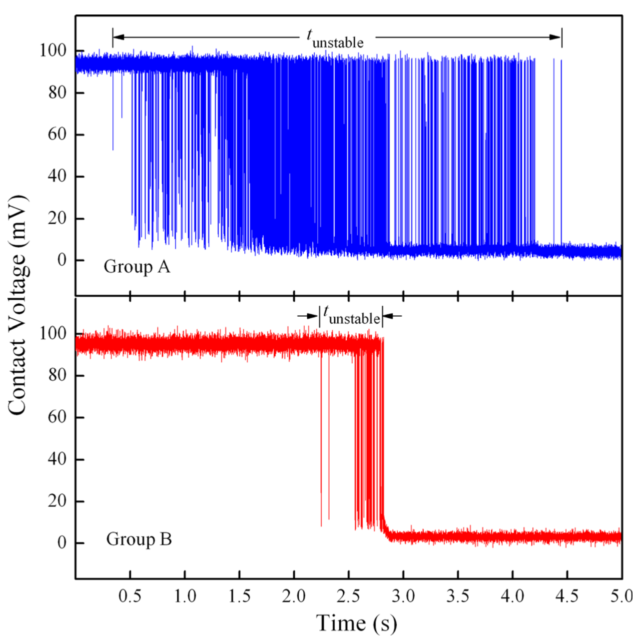

FIG. 1. Contact voltage versus loading time of two typical Au-to-Au contact tests in group A (exposed in MEMS fabrication environment) and group B (reference group, untreated). The duration of the unstable region is denoted as $t_{unstable}$.

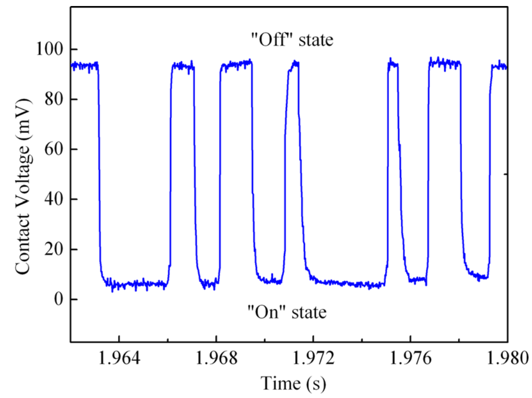

FIG. 2. A close look for a typical contact voltage versus loading time curve measured from a sample in group A. A two-level RTS with "on" and "off" states is shown.

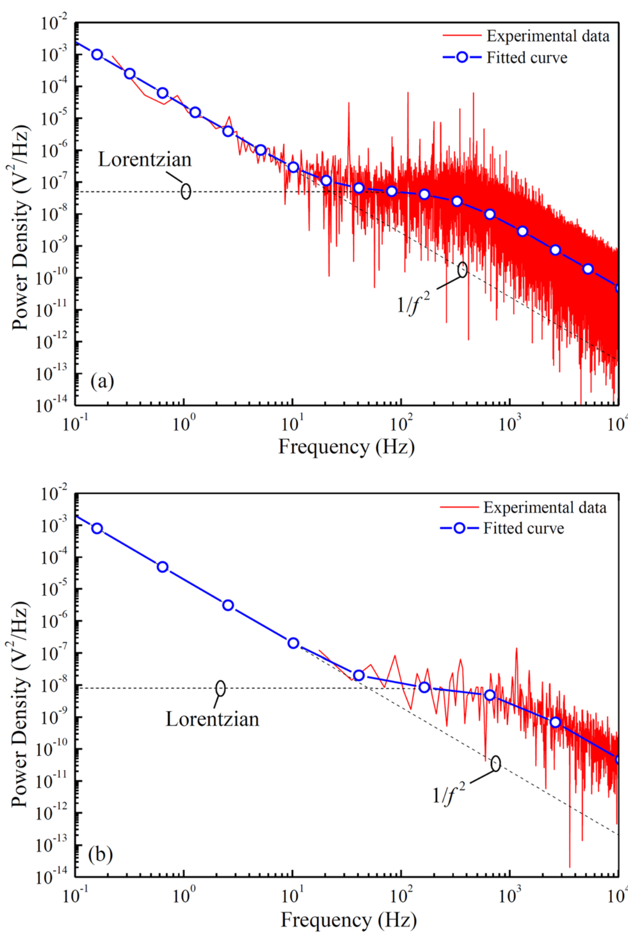

FIG. 3. PSD of the conduction noise in the unstable region for Au-to-Au contacts measured from the samples in (a) group A and (b) group B. The experimental data are fitted by superimposing $1/f^2$ and Lorentzian components (dashed lines).

$$\frac{S_N}{N^2} = \frac{S_I}{I^2} = \frac{S_V}{V^2} = \frac{1}{N^2} \frac{4{\tau_p}^2}{(\tau_t + \tau_d)[1 + (2\pi f \tau_p)^2]}, \tag{1}$$

where τ_t and τ_d are average trapping and detrapping times, respectively; τ_p is the relaxation time in the correlation function, with $1/\tau_p = 1/\tau_t + 1/\tau_d$; N is the total number of free charge carriers. For the electron tunneling through the alien layer via the mid-gap traps, we would expect a small discrepancy between the trap energy and the Fermi level, and thus similar values of the average trapping and detrapping time.[15] Substituting $\tau_t = \tau_d = 2\tau_p$ into Eq. (1), we have

$$\frac{S_V}{V^2} = \frac{1}{N^2} \frac{\tau_p}{1 + (2\pi f \tau_p)^2}. \tag{2}$$

Indeed, the PSD of the contact voltage noise in Fig. 3 for both group A and group B samples can be well fitted by superimposing a Lorentzian noise component in conjunction with a $1/f^2$ noise. The $1/f^2$ noise can be attributed to the resistance fluctuation of the contact metal, as a result of inhomogeneous local conductivity.[14]

For the samples of group A and group B in Fig. 3, the number of carriers (N) and the relaxation time (τ_p) can be extracted based on the experimental data with the abovementioned two noise components. This allows us to estimate trap density (n_t) at the contact interface based on the radius of effective contact area a, which can be determined from the electrical contact resistance R_c at the ending point of the unstable region as a first order approximation.[16] Using electron mean free path of 38 nm in Au and electrical contact resistivity of $3.6 \times 10^{-8}\ \Omega$ m,[17] the relaxation time (τ_p) and the trap density (n_t) at the contact interface are obtained to be 0.5 ms, $3.6 \times 10^{19}/\text{cm}^3$ and 0.2 ms, $2.9 \times 10^{19}/\text{cm}^3$ for group A and group B, respectively. The reduced relaxation time implies a faster trapping-detrapping process, which could be due to the thinner alien film on the contact surface for the sample from group B. The trap density values agree well with the previous experimental measurements of the trap density in polymers used for microfabrication process, which ranges from 2×10^{19} to $7 \times 10^{19}/\text{cm}^3$.[18,19]

In conclusion, the electrical conduction noise of Au-to-Au microcontact in the unstable contact region has been characterized and analyzed to gain a fundamental understanding of the role of align film on the contact behavior at the initial contact stage. A Lorentzian type low frequency noise component, which could be associated with the electron trapping and detrapping in the alien layer located at the contact interface, is identified and analyzed. The results provide further insights to properties of the hydrocarbon alien layers that are widely presented at metal contact surfaces in MEMS devices.

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