

Long range diffusion noise in platinum microwires with metallic adhesion layers

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(Received 26 March 2007; accepted 14 May 2007; published online 6 June 2007)

Voltage fluctuations of platinum wires hosted by silicon nitride beams were investigated. The authors considered four variants of the wires: three with an adhesion layer and one without an adhesion layer. They found that the presence of an adhesion layer changes the nature of the power spectrum which is $1/f$ for wires with no adhesion layers and $1/f^{3/2}$ for wires with an adhesion layer. They attribute the value of the exponent $\alpha=3/2$ found in wires with adhesion layers to the long range diffusion of oxygen atoms along the interface between the adhesion layer and the platinum layer. © 2007 American Institute of Physics. [DOI: 10.1063/1.2746961]

Low frequency electrical noise in metallic films has been extensively investigated.¹⁻³ In a variety of metallic films, the resulting noise spectra are frequency dependent and are known as $1/f^\alpha$ spectrum with the exponent $\alpha \approx 1$. An important body of research into the origin $1/f$ noise has emerged but a unifying picture is still lacking. In the Dutta-Horn picture,¹ $1/f$ noise arises from equilibrium defect fluctuations associated with the defects' motion which is thermally activated and nondiffusive. These fluctuations have a characteristic time scale t_c which is itself sampled from a distribution function. Other spectra of the form $1/f^\alpha$ were $\alpha \neq 1$ were also found. In particular, the value of $\alpha=3/2$ was attributed to transport noise such as long range diffusion in metallic films⁴⁻⁶ with hydrogen impurities. This form of the spectrum was also found in silver films subject to electromigration damage,⁷ where it was argued that $1/f^{3/2}$ spectrum is attributed to the long-range diffusion of atoms through pathways opened during electromigration damage.

The present work is concerned with the investigation of the noise spectrum of a velocity sensor.⁸ The sensor consists of two freely suspended silicon nitride beams on the top of which a double layer of platinum and an adhesive metallic layer (adhesion layer) are deposited by sputtering. We show that the presence of the adhesion layer changes the nature of the power spectrum of the voltage fluctuations of the wires. Without the adhesion layer, the low frequency noise follows a power law with the usual power spectrum $1/f^\alpha$, with $\alpha \approx 1$. The presence of the adhesion layer, changes this power spectrum to $1/f^\alpha$ with $\alpha \approx 3/2$. We attribute this effect to the long range diffusion of oxygen atoms along the interface between the adhesion layer and the platinum.

To fabricate the velocity sensor, we consider four variants: three variants were made by depositing a 10 nm adhesion layer of chromium (Cr), titanium (Ti), and tantalum (Ta), respectively, followed by a deposition of 150 nm of platinum. These variants will be referred to as Pt/Cr, Pt/Ti, and Pt/Ta. The fourth variant consists of a device without an adhesion layer; thus a layer of 150 nm is deposited directly on silicon nitride. This variant will be referred to as Pt/SiN.

All films were deposited in a dc magnetron sputtering system. The system has a rotating substrate holder, with a distance of about 18 cm between the substrate and target. After the deposition of the adhesion layers, the samples stayed *in vacuo* prior to the deposition of the platinum film. After patterning and etching, the resistors were released with dimensions of 1 mm in length and 4 μm in width. Prior to experiments, the sensors were annealed at 500 °C. They consisted of two wires which are 200 μm apart. The resistance of the wires was 300 Ω at room temperature. As a reference in the experiments, a common metal film resistor of 300 Ω was used. The output signal was amplified twice by two amplifiers with an amplification factor of 50 dB. The signals were recorded by a 20 bits analog-to-digital converter with an input impedance of 30 k Ω , and a flat frequency response in the bandwidth (30 Hz, 20 kHz). The recorded signal was digitized and analyzed in a personal computer. The temperature of the wires was varied from 293 to 646 K, and the spectrum of the detected output signal (in V^2/Hz) at each temperature was computed. In Fig. 1 we show the frequency dependence of the power spectrum of the voltage fluctuations for Pt/SiN and Pt/Ta at temperatures 400 and 477 K, respectively. The power spectrum scales with frequency as $S_V(f) \sim 1/f^\alpha$ for frequencies below 3 kHz for Pt/Ta and below 2 kHz for Pt/SiN. The values of α are $\alpha \approx 0.90$ and $\alpha \approx 1.5$ for Pt/SiN and Pt/Ta, respectively. These values were determined by a regression fit on a double logarithmic plot of the power spectrum versus frequency. The flat portions of the spectrum correspond to white noise level. The value of $\alpha \approx 1$ was also observed by Scofield *et al.*² for 142 nm thick platinum on sapphire at 400 °C.

For all wires (Pt/Ta, Pt/Ti, Pt/Cr, and Pt/SiN) the power spectrum follows the power law scaling $S_V(f) \sim 1/f^\alpha$. For wires with an adhesion layer, the scaling was observed over a range of two orders of magnitude in frequency and the value of the exponent α was found to be close to 3/2. We found this exponent to be temperature independent (within the error range) over the considered temperature range, as shown in Fig. 2.

The values of α found in all wires with an adhesion layer are consistent with the value found for resistance fluctuations

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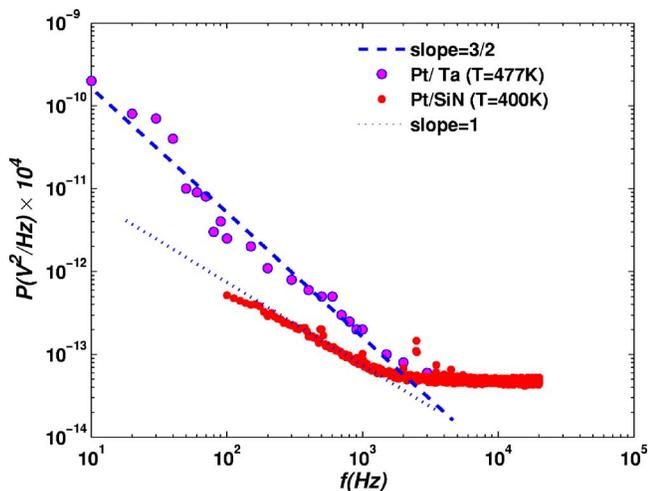


FIG. 1. (Color online) Voltage fluctuations power spectrum of Pt/Ta and Pt/SiN systems at $T=477$ K and $T=400$ K, respectively. The value of $\alpha \approx 3/2$ was common to all films with an adhesion layer. For comparison, we plot two lines with slopes $3/2$ and 1 , respectively. The linear regression fit to the data in the scaling range, gives slopes of 1.5 ± 0.03 and 0.9 ± 0.02 for Pt/Ta and Pt/SiN, respectively.

in niobium films⁴ $\alpha=3/2$. Scofield and Webb⁴ proposed that hydrogen diffusion in niobium films modulates the resistance of the films where fluctuations of the number of hydrogen ions in the film segment induce the fluctuations of the resistance, i.e., $\delta r \propto \delta N$, where the fluctuation δN obeys the diffusion equation in the fixed volume of the film's segment. In the framework of this model,⁴ a diffusing species in the film of length L , will generate a power spectrum of the form $fS_V(f)/\langle \delta V^2 \rangle = 2P(x) - P(2x)$, where $x = (f/f_c)^{1/2}$, $f_c = D_0 \exp(-E/K_B T) / \pi L^2$ and

$$P(x) = (1 - e^{-x}(\sin x + \cos x)) / (\pi x). \quad (1)$$

Here, $\langle \delta V^2 \rangle$ is the voltage variance. We first assume that the fluctuations in the wires with the adhesion layer are described by the one dimensional diffusion process mentioned above and focus on the Pt/Ta wires. To determine the characteristic frequency f_c for Pt/Ta, we perform a nonlinear regression fit of the data to the theoretical expression of the one dimensional power spectrum (1) in the working frequency range of the sensor. In Fig. 3 we show the plot of

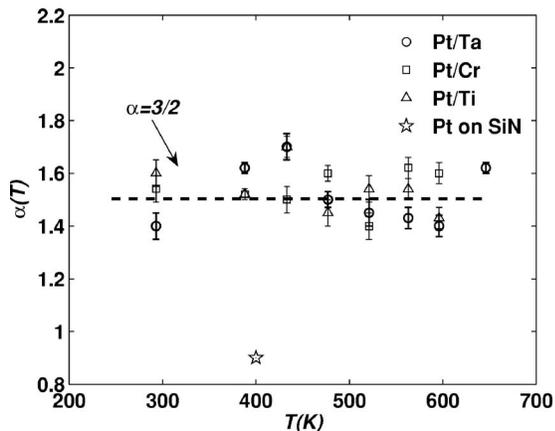


FIG. 2. Plot of the exponent α as a function of the temperature for wires with and without an adhesion layer. Wires having an adhesion layer have a value of α consistent with the value of $3/2$ arising from the long range diffusions.

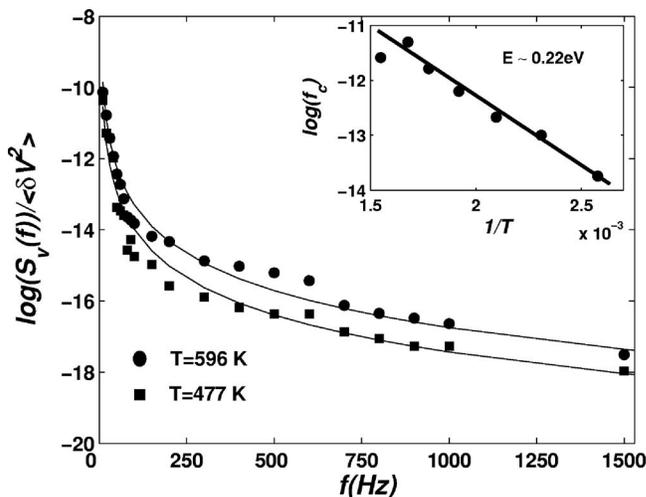


FIG. 3. Plot of $\log(S_V(f)/\langle \delta V^2 \rangle)$ vs f for Pt/Ta. The solid lines are the fit to the theoretical power spectrum. The inset shows $\log(f_c)$ vs $1/T$.

$\log(S_V(f)/\langle \delta V^2 \rangle)$ versus f as well as the theoretical fit to the data for two different temperatures $T=596$ K and $T=477$ K. We have determined the characteristic frequency at various temperatures: 596, 563, 521, 477, and 433 K. The inset of Fig. 3 shows the plot of the logarithm of f_c versus $1/T$, the slope gives the activation energy, and the intercept gives the diffusion coefficient preexponential factor for Pt/Ta, which are $E_{Pt/Ta} \approx 0.22 \pm 0.04$ and $D_0 \approx 2.4 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$ for $L=1$ mm. The value found for the activation energy is very close to the value derived directly from the semilogarithmic plot of $S_V(40 \text{ Hz})$ (Fig. 5) as a function of $1/T$, which is related to $E_{Pt/Ta}$, by the relation $E'_{Pt/Ta} = (3/2)E_{Pt/Ta}$. We found $E'_{Pt/Ta} = 0.35 \pm 0.02$ eV which gives $E_{Pt/Ta} = 0.23 \pm 0.01$ eV. The evidence of the diffusion process can be shown by plotting $\log(f_c S_V(f, T))$ versus $\log(f/f_c(T))$ (Fig. 4) at different temperatures for Pt/Ta wires, which shows a data collapse into a single curve, as expected from a diffusion process.

In Fig. 5 we plot the logarithm of the quantity $\Omega(T) = f^\alpha S_V(f)$ as a function of $1/T$ at 40 Hz. The plots corresponding to wires with an adhesion layer are reminiscent of a thermally activated process. The activation energies

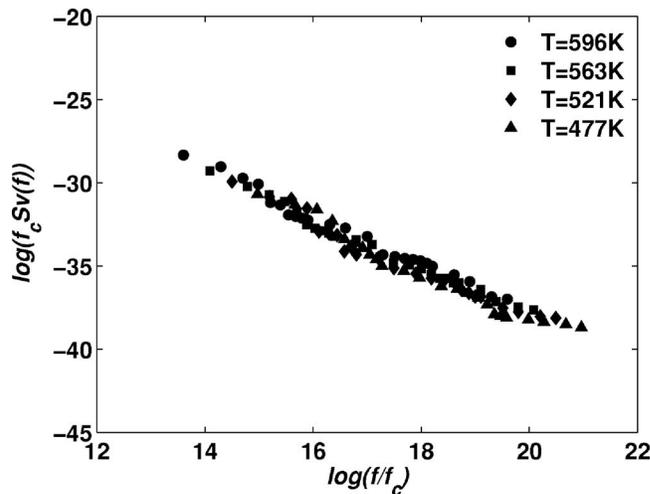


FIG. 4. Plots of $\log(f_c S_V(f, T))$ vs $\log(f/f_c(T))$ for Pt/Ta wire at different temperatures showing the collapse of the data on a single curve as predicted by the diffusion model.

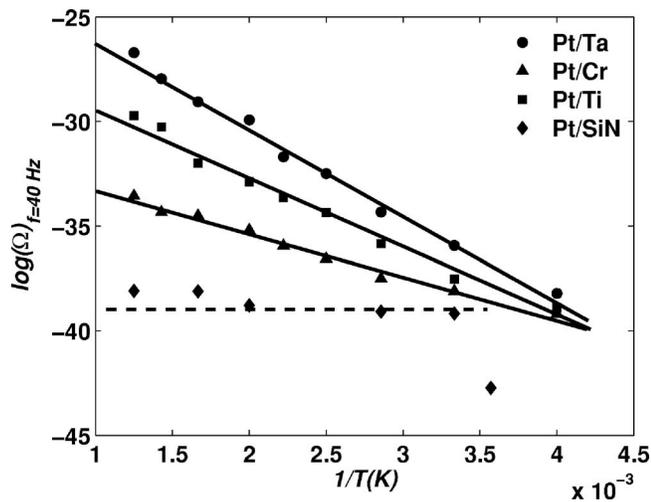


FIG. 5. Plots of $\Omega(T)=f^\alpha S_V(f)$ vs $1/T$ showing a thermally activated process in films with an adhesion layer.

found for Pt/Ti and Pt/Cr wires are 0.190 ± 0.02 eV and 0.118 ± 0.01 eV, respectively. No evidence of a thermally activated process was found in wires with no adhesion layer as clearly noticed in Fig. 5. The value of the activation energy found for the Pt/Ta wires is very close to the value found in niobium films (≈ 0.23 eV), which was attributed to hydrogen diffusion in wires.⁴ The evidence of a diffusive process in wires with an adhesion layer suggests that impurities, mainly hydrogen and oxygen, modulate the wires resistance. In our case, a strong candidate for this process is oxygen since at high temperature (above 600 K), hydrogen is easily effused off the wires and the exponent α still maintains its value of 3/2. Ambient oxygen can freely penetrate the wires through the platinum layer through grain boundaries. All three wires with adhesion layers have in common the formation of oxides at the interface. In Pt/Ti films, ambient oxygen and titanium can diffuse through platinum films where they undergo chemical reactions to form TiO_x (Refs. 9 and 10) or $PtTi_x$ components. It was also reported that for thin titanium layers, the titanium oxide phase is located at the boundaries of platinum grains.¹⁰ Tantalum hardly diffuses into the Pt

layer and, consequently, the oxidation of Ta occurs mainly at the interface Pt/Ta.¹¹ As a result, stress induced defects are less present in Pt/Ta in comparison with Pt/Ti. Whereas chromium also has these effects (as for Pt/Ti), it also has a strong tendency to react with Pt to form an eutecticum, even at rather low temperatures.¹² We believe that oxides formed at the interface act as scattering points and that different activation energies are associated with the different natures of oxide scatterers at the interface. The absence of the long range diffusion in the Pt without an adhesion layer suggests that there is no oxide formation at the interface and, consequently, no scattering process of oxygen. However, further investigations are needed to confirm this assumption. Nevertheless, the present work shows that there is less excess noise in Pt without an adhesion layer than in Pt with an adhesion layer. The values of the diffusion coefficient for Pt/Ta provide evidence of an enhanced diffusion process, since these values are much larger than the values found for the bulk platinum.¹³

The authors would like to thank R. Tiggelaar for useful discussions.

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