Long range diffusion noise in platinum micro-wires with metallic adhesion layers

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Voltage fluctuations of Platinum wires hosted by silicon nitride beams were investigated. We considered four variants of the wires: three with an adhesion layer and one with no adhesion layer. We 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. We attribute the value of the exponent $\alpha = 3/2$ to the long range diffusion of trapped hydrogen in the wires.

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Low frequency electrical noise in metallic films has been extensively investigated\cite{1,2}. In a variety of metallic films, the resulting noise spectra are frequency dependent and are known as $1/f^\alpha$ spectrum with the exponent $\alpha \simeq 1$. 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, $1/f$ noise arises from equilibrium defect fluctuations associated with the defects's motion which is thermally activated and non-diffusive. 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 films\cite{3,4,5} with hydrogen impurities. This form of the spectrum was also found in silver films subject to electromigration damage\cite{6}, 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\cite{7}. 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 $\alpha \simeq 1$. The presence of the adhesion layer, changes this power spectrum to $1/f^\alpha$ with $\alpha \simeq 3/2$. We attribute this effect to the long range diffusion of hydrogen trapped in the Pt/adhesion layer structure.

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 consist of a device without an adhesion layer thus a layer of 150 nm 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 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 $\mu$m in width. Prior to experiments, the sensors were annealed at 500$^\circ$C. They consisted of two wires which are 200 $\mu$m apart. The resistance of the wires was 300 $\Omega$ at room temperature. As a reference in the experiments, a common metal film resistor of 300 $\Omega$ 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 AD-converter with an input impedance of 30 K$\Omega$, and a flat frequency response (30 Hz, 20 kHz). The recorded signal was digitized and analyzed in a personal computer. The temperature of the wires was varied from 293 K to 646 K, and the spectrum of the detected output signal (in V$^2$/Hz) at each temperature was computed. In figure\cite{1} we show the frequency dependence of the power spectrum of the voltage fluctuations for Pt/SiN and Pt/Ta at temperatures 400 K and 477 K respectively. The power spectrum scales with frequency as $S_V(f) \sim 1/f^\alpha$ for frequencies below 3kHz for Pt/Ta and below 200 Hz for Pt/SiN. The values of $\alpha$ are $\alpha \simeq 0.90$ and $\alpha \simeq 1.62$ 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 $\alpha \simeq 1$ was also observed by Scofield and Mantes 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 $\alpha$ was found to be close to $3/2$ as shown in figure\cite{2}. This exponent We found to be temperature-independent (within the error range) over the considered temperature range.

The values of $\alpha$ found in all wires with an adhe-
where the fluctuation $\delta N$ work of this model in the fixed volume of the film’s segment. In the framework of this model, a diffusing species in the film of length $L$, will generate a power spectrum of the form $fS_V(f)/<\delta V^2> = 2P(x) - P(2x)$, where $x = (f/f_c)^{1/2}$, $f_c = D_0 \exp(-E/K_B T)/\pi L^2$ and

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

here, $<\delta V^2>$ 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 \cite{1} in the working frequency range of the sensor. In figure 2 we show the plot of $\log(S_V(f))/(<\delta V^2>)$ versus $f$ for two different temperatures $T = 596K$ and $T = 477K$. The inset of figure 2 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 $E_{Pt/Ta} ≃ 0.22 ± 0.04$ and $D_0 ≃ 2.4 \times 10^{-5} \text{cm}^2 \text{s}^{-1}$ for $L = 1mm$. The value found for the activation energy is very close to the value derived directly from the semi-logarithmic plot of $S_V(40Hz)$ (figure 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 $E_{Pt/Ta} = 0.35 ± 0.02 eV$ which gives $E_{Pt/Ta} ≃ 0.23 eV$. The evidence of the diffusion process can be shown by plotting $\log(f_cS_V(f,T))$ versus $\log(f/f_c(T))$ (figure 4) at different temperatures for Pt/Ta wires, which shows a data collapse into a single curve, as expected from a diffusion process.

In figure 4 we plot the logarithm of the quantity $\Omega(T) = f^{\alpha}S_V(f)$ as a function of $1/T$ at $40Hz$. The plots corresponding to wires with an adhesion layer are reminiscent of a thermally activated process. The ac-

FIG. 1: Voltage fluctuations power spectrum of Pt/Ta and Pt/SiN systems at $T=477K$ and $T=400K$ respectively. The value of $\alpha \simeq 3/2$ was common to all films with an adhesion layer. For clarity, these curves are shifted by few orders of magnitude.

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

FIG. 3: plot of $\log(S_V(f))/<\delta V^2>$ versus $f$ for Pt/Ta. The solid lines are the fit to the theoretical power spectrum. the inset shows $log(f_c)$ versus $1/T$.
Evidence of a thermally activated process was found in the data on a single curve as predicted by the diffusion model.\(\Omega(T) = f^{\alpha}S_{V}(f) = \frac{f^{\alpha}S_{V}(f)}{T} \) versus \(1/T(K)\) for Pt/Ta wire at different temperatures showing the collapse of the data on a single curve as predicted by the diffusion model. 

![Image](image_url)

**FIG. 4:** Plots of \(\log(fS_{V}(f,T))\) versus \(\log(f/f_{c}(T))\) 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.

The value of the activation energy found for the Pt/Ta wires is very close to the value found for trapped hydrogen in Niobium films (\(\approx 0.23\) eV). Hydrogen can be trapped in metals by a variety of defects such as voids, high strain field around dislocations, grain boundaries or impurities\(^{10}\). Evanescent trapping of hydrogen by these defects increases the activation energy to \(E = E_{0} + E_{b}\), where \(E_{0}\) is the activation energy in the absence of traps and \(E_{b}\) is the energy associated with traps. Thin films such as those studied here have different structure than bulk metals. In Pt/Ti films, ambient oxygen and titanium can diffuse through platinum films where they undergo chemical reactions to form TiO\(^{11,12}\) 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\(^{13}\). Tantalum hardly diffuses into the Pt layer, and consequently the oxidation of Ta occurs mainly at the interface Pt/Ta\(^{13}\). 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\(^{14}\). We believe that the observed diffusion possess originates from the trapped hydrogen in the wires and that different activation energies are associated with the difference in the nature of scattering defects in each wire. The trapped hydrogen in the wires might originate from sputtering or processing of the sensors. For example, it is well-known that significant amounts of hydrogen are produced during KOH-etching; this is used to release the SiN-beams. The absence of the long range diffusion in the Pt without an adhesion layer suggests that hydrogen does not undergo long range diffusion in this wire. In fact, hydrogen effusion is very likely during high temperature annealing, which is facilitated by the porous nature of Pt subject to high temperatures. Our experiments show that there is less excess noise in Pt without an adhesion layer than in Pt with an adhesion layer. The noise in Pt wires is \(1/f\) and no evidence of thermal activation of this process was observed. This can not be explained by the "defect motion" model of Dutta-Horn. The authors would like to thank R. Tiggelaar for useful discussions.

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