$1/f$ noise in polycrystalline silicon thin films

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In this paper, an approach is presented to explain $1/f$ noise in polycrystalline silicon thin films. This approach is based on the finding that the grain boundary has a leading part in the generation of noise. In this context, $1/f$ noise is explained as a thermal noise due to dielectric losses in the grain boundaries, and modeled using physical parameters linked with the quality of the material at the grain boundary. Experimental results on highly boron-doped polysilicon resistors are presented. In order to support the thermal origin of $1/f$ noise in our samples, results on another simple device that generates $1/f$ noise are presented. [S0163-1829(98)04519-6]

I. INTRODUCTION

In recent years, the use of polysilicon in microelectronics has increased, mainly as gate electrodes in metal-oxide-semiconductor integrated circuits. Low or moderately doped n-type polysilicon films have been largely studied and used. With the development of micro-electro-mechanical systems, studies on polysilicon films are again necessary. Because of their tendency to segregation, phosphorus and arsenic impurities are avoided. Boron-doped p-type films are preferred, and widely used in silicon pressure sensors based on etched diaphragm and polysilicon resistors. The films must in this case be highly doped to ensure good characteristics to the sensor. In order to improve these characteristics, it is then necessary to study the noise in highly boron-doped polysilicon resistors.

The existing models of $1/f$ noise in polysilicon films, like Luo and Bosman's[1] or Jang's,[2] are of outstanding importance, but adapted to specific doping levels and type, and they cannot be extended to our highly boron-doped films. Moreover, what is particular with pressure sensors is that they can be submitted to chemical corrosion. A study of the effect of chemical corrosion on $1/f$ noise in this kind of resistor is in progress.[3] It has been shown that highly boron-doped resistors develop a large amount of $1/f$ noise at low frequencies, and that the level of this $1/f$ noise depends significantly on the corrosive atmosphere. This fact shows that the physical origin of $1/f$ noise must be localized in the areas mainly deteriorated by corrosion.

In this paper, an approach is presented to characterize the low-frequency noise observed in our samples. This approach is based on the very general fact that materials included in grain boundaries show dielectric losses. These losses are a dissipation term for fluctuations of the electrical transport rarely taken into account in literature, as far as we know.

II. THEORY

The aim is first of all to understand the phenomena involved in electrical transport better. This should allow us to characterize precisely static and dynamic (i.e., fluctuations) characteristics of polysilicon. In these thin films, only two sorts of dissipation can occur: dissipation by the Joule effect, and dielectric losses. The Joule effect mainly occurs in the bulk of the grain, but dielectric losses can be situated in the grain boundaries. Since these boundaries are preferential places for corrosion, we have focused on dielectric dissipation to explain $1/f$ fluctuations.

From the static point of view, a grain boundary is a very thin dielectric barrier which can easily be crossed by tunneling. Since the voltage is low on the bounds of the grain boundary, tunneling is expressed by a constant resistance.[4] At high polarization levels, usually used in static measurements, the polysilicon film behaves as a normal resistor, but its resistivity is higher than what is expected for a nongranular silicon of the same doping level. This is of course due to the tunnel effect necessary for the electrical transport, which has to be considered.

On the other hand, the dynamic behavior is quite different due to the low oscillating voltage involved. At these levels and in alternative regimes, hysteresis can occur in the dielectric material of the grain boundary, and has to be taken into account. An electrical equivalent scheme of the polysilicon film has to consider these remarks. The grain bulk can be symbolized by a resistor R_V. Its value can be deduced from the resistivity of monocrystalline silicon of a similar doping level and type. It is also possible to take into account the doping segregation effect[5] by reducing the doping level considered for the value of R_V. This resistor leads to white thermal noise. Connected in series with R_V, a capacitor can be used to symbolize the dielectric barrier. This capacitor will of course have a leakage resistor R in parallel in order to represent the dissipation by the Joule effect in the dielectric material. This leakage resistor contributes to white thermal noise.

Dielectric dissipation in the grain boundaries is linked, for example, with the presence of trapped ionized particles. In Fig. 1, we take as an example a positive particle trapped in the grain boundary. The particle can be situated, for example, in two nearly states. The potential barrier separating these positions is supposed to be not very important compared to kT. If an electric field is applied to the grain boundary, the particle will then be able to pass over the barrier, as illustrated in Fig. 1. The possibility for this particle to oscillate between the two positions induces energy dissipation.

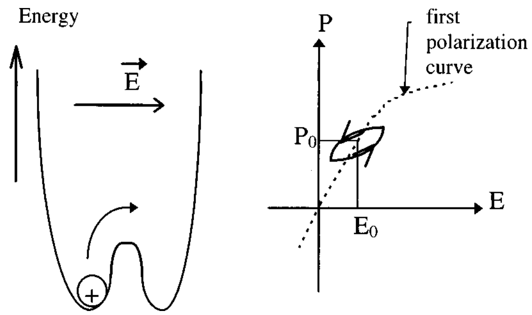

FIG. 1. The possibility for an ionized trapped particle to oscillate between two positions leads to dielectric dissipation.

From the macroscopic point of view, this is represented by hysteresis on the polarization against the electric-field diagram of the dielectric material.[6,7] This hysteresis agrees with the general approach of Keshner, who said that ''1/*f* processes do have memory.''[8] The area of the hysteresis loop represents energy dissipated due to this hysteresis. As it is generally agreed in literature, for low levels of the oscillating voltage V the dissipated power is proportional to V^2, and to f, where f is the frequency at which the cycle is run. It can then be represented by a resistance inversely proportional to f. We will then symbolize the dielectric losses by a resistor in parallel with the capacitor with a value of r/f, where r (in $\Omega\ \mathrm{s}^{-1}$) depends on the bias level. The general scheme is represented in Fig. 2. The grains and grain boundaries are all connected in series, thus leading for the whole thin film to an electrical scheme similar to Fig. 2.

Using the fluctuation and dissipation theorem and that of Nyquist, the level of noise in our thin film is then given by the voltage fluctuation spectral density S_V (V^2/Hz):

$$S_V = 4kX(f), \tag{1}$$

where $X(f)$ is the dissipative part of the impedance defined in Fig. 2. A complete calculation of $X(f)$ in Eq. (1) gives

$$S_V = 4kT\left[R_V + R\,\frac{r}{f}\,\frac{R+\dfrac{r}{f}}{R^2(1+4\pi^2r^2C^2)+2R\,\dfrac{r}{f}+\left(\dfrac{r}{f}\right)^2}\right]. \tag{2}$$

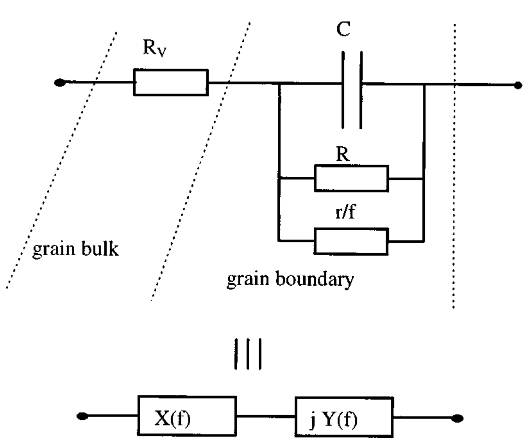

FIG. 2. Equivalent dynamic electric scheme of the polysilicon resistor for the noise generation.

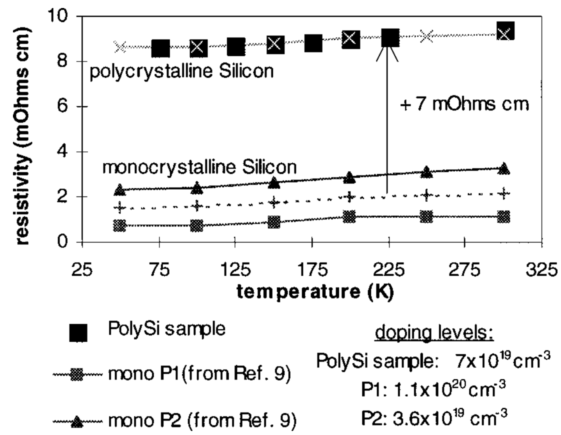

FIG. 3. Comparison of the resistivity vs temperature curves of our polysilicon sample (boron doped at 7×10^{19} at. cm^{-3}) and monocrystalline silicon with a similar doping level (from Ref. 9).

If, in the grain boundary, dissipation by the Joule effect is more important than dissipation by hysteresis, that is, if R is smaller than r/f, Eq. (2) can be simplified. The resulting noise is white noise plus $1/f^2$ noise. That is not what is observed in our samples. Conversely, if the dielectric losses are the main source of dissipation, Eq. (2) is simplified in Eq. (3):

$$S_V = 4kT\left[R_V + \frac{r}{\gamma}\,\frac{1}{f} + \frac{r^2(1-2/\gamma)}{R\gamma}\,\frac{1}{f^2}\right] \tag{3}$$

at first order, where $\gamma = 1+4\pi^2r^2C^2$. This shows that hysteresis dissipation leads to $1/f$ noise.

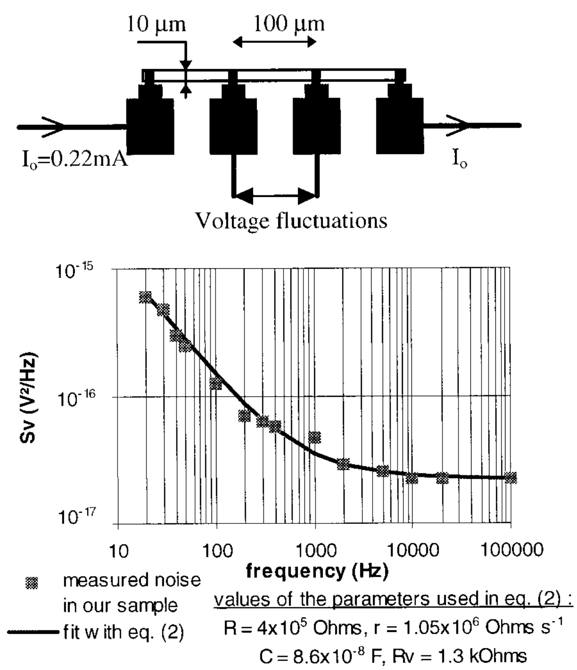

FIG. 4. Example of a voltage power spectral density spectrum and the corresponding fit ($T=300$ K) with Eq. (2) obtained for a biasing current of 0.22 mA.

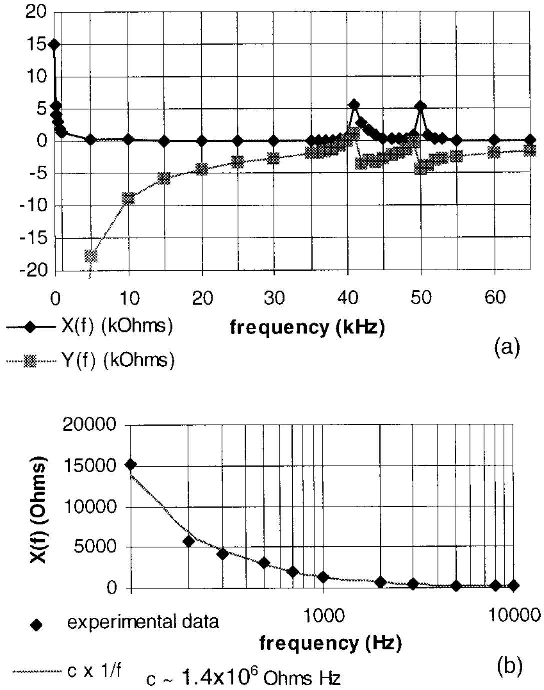

FIG. 5. Measured impedance of the piezoelectric transducer: $X(f)$ is the dissipative part, and $Y(f)$ is the reactive part. (a) Full scale impedance up to 65 kHz. (b) Low-frequency representation of $X(f)$ showing the $1/f$ evolution.

III. SAMPLE DESCRIPTION AND EXPERIMENTAL RESULTS

The polysilicon samples used in our study were prepared as follows. A 5000-Å-thick SiO_2 layer was thermally grown on a 2-in. silicon wafer. An undoped polysilicon thin film was then deposited on top of the SiO_2 layer at 625 °C by low-pressure chemical vapor deposition to an average thickness of 5000 Å. A boron dose of 4×10^{15} cm^{-2} was then implanted at 60 keV in the polysilicon. The samples were annealed at 975 °C for 30 min in N_2 to insure a uniform doping distribution of 7×10^{19} cm^{-3}. After that, the polysilicon was patterned. No oxide layer was then deposited, in order to allow chemical corrosion of the polysilicon film. A 1-μm-thick aluminum film was deposited and patterned. Finally, the film was annealed at 450 °C for 30 min to ensure Ohmic contacts.

The entire sample realization was performed in the CIME facilities (Grenoble, France). The sample under study is a four-contact resistor. Its dimension is 300×10 μm^2, thus leading to a total static resistance of 5.8 kΩ at room temperature. The contact resistance was found to be around 11 Ω, and is thus negligible in front of the total value of the resistor.

First, a measurement of the resistivity of the sample at low temperature was performed using a low-frequency impedance analyzer HP 4192A and a liquid-helium cryostat. Measurements were realized from 75 K up to 300 K. The results were then compared to those of Chapman *et al.* for monocrystalline silicon of similar doping level and type.[9] As shown in Fig. 3, the evolution versus temperature is very similar. But the general resistivity level is higher for polysilicon. By adding a constant of approximately 7 mΩ cm to

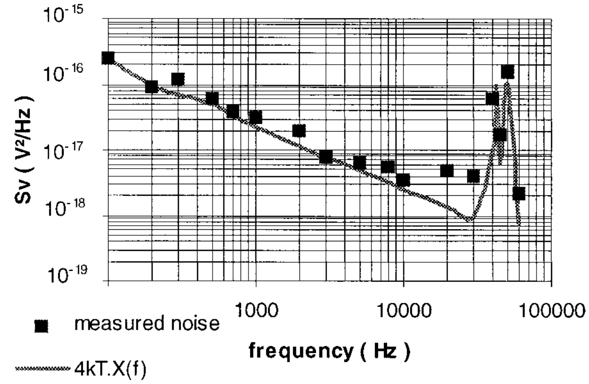

FIG. 6. Comparison of the measured noise and the expected thermal noise in the piezoelectric transducer.

the values of the monocrystalline silicon, it is possible to fit our results. Then, at low temperatures, the conduction in our sample can be described as follows: conduction in the bulk of the grains as in monocrystalline silicon of the same doping level (same evolution versus temperature), and tunneling through the grain boundaries. According to Ref. 4, the barrier resistivity observed of 7 mΩ cm is explainable by the presence of a 5-Å-thick dielectric film of an energy gap of about 10 eV. Then this value of 7 mΩ cm is physically adequate.

Noise measurements were performed at room temperature using a low noise preamplifier LI-75A of NF Electronic Instruments, and a digital spectrum analyzer TakedaRiken 9405 A. When necessary, the noise of the measurement system was deduced. The four-contact resistor was biased using low-noise Cd-Ni batteries. The voltage fluctuations were measured at the two contacts not crossed by the bias current. The samples develop $1/f$ noise at low frequencies. A typical spectrum obtained for a current of 0.22 mA is given in Fig. 4. The sample presents $1/f$ noise at frequencies below 1 kHz. Beyond this frequency, only thermal white noise is observed. The model developed allows a good fit of the experimental spectrum, thanks to the complete equation (2). The parameters involved are physically acceptable. In particular, R and C lead to a value of 34 ms for the dielectric time constant, which is adequate for a poor quality dielectric.

In our samples, the fact that the impedance varies with frequency is only observable in noise measurements. As a matter of fact, if we consider the conduction of the polarization current through the grain boundary, the main current is tunneled. Since this mechanism does not lead to dissipation, it is not ''seen'' in noise measurements, thus revealing the existence of dielectric losses.

IV. DISCUSSION

What is a little frustrating with our samples is that we cannot check experimentally that $1/f$ noise is a thermal noise, as the main current is tunneled. But other displays exist that can allow such a verification. As an example, we have considered a cheap piezotransmitter (TUE4016). The ceramic material used for the piezoelectric capacitor usually develops important dielectric losses. Moreover, since the capacitor is macroscopic, the tunnel effect is expected to be negligible.

First, we measured at room temperature the impedance of such a transmitter using the impedance analyzer HP 4192 A, from 100 Hz to 60 kHz. The dissipative part of this impedance $X(f)$ shows a $1/f$ dependence at frequencies below 10 kHz. At 42 and 50 kHz, two resonance peaks were observed. They correspond to the mechanical resonance of the transmitter, which is effectively an ultrasound emitter. These impedance measurements are given in Fig. 5. Then the noise was measured at the same temperature without any bias applied. In Fig. 6, we compare the measured noise and the expected thermal noise $4kTX(f)$. The fit between the two quantities is quite good for the $1/f$ behavior (dielectric dissipative term) and for the resonance term (the mechanical dissipative term).

V. CONCLUSIONS

It has been shown that it is possible to explain the $1/f$ noise developed by polycrystalline thin films from considerations of the dielectric properties of grain boundaries. The noise developed agrees with a thermal origin, and its dependence on frequency is explained thanks to the generalized Nyquist's theorem. Results presented concerning the ultrasound emitter validate the hypothesis of a thermal origin for $1/f$ noise.

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