Deep-level-noise spectroscopy of ion-implanted polysilicon thin films

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Noise measurements represent a new technique for the characterization of traps in polycrystalline silicon. Data of highly-boron-doped polysilicon thin films reveal that the noise can be decomposed into a small number of Lorentz spectra. Each of these Lorentzian curves corresponds to a specific trap in the space-charge regions of the grain boundaries. We therefore introduce deep-level-noise spectroscopy (DLNS) as a new quantitative tool for the analysis of bulk traps in polysilicon. DLNS is based on temperature-dependent noise measurements at different frequencies. Our quantitative analysis yields the energy position, the capture cross section, as well as the concentration of each trap.

I. INTRODUCTION

Thin films of polycrystalline silicon now find widespread use in microelectronics.[1] The technological importance of these films is, however, still contrasted by incomplete knowledge about their electronic and structural properties.[2] For example, the meaningfulness of such basic semiconductor characterization techniques as the Hall effect or thermopower measurements is still not yet fully understood. These techniques were originally designed for single crystals; in polycrystals these techniques average somehow (and possibly even differently) over the electronic properties of the grains as well as of the grain boundaries when used for polycrystalline semiconductors.[3,4]

Improved understanding of polysilicon therefore requires characterization techniques that are specifically designed for the grain boundaries as well as for the grains. Recent techniques based on photoconductivity,[5] current-voltage curves,[6] noise,[7] or ac admittances[8] were all designed for single grain boundaries in *bicrystals*. Most of these methods can unfortunately not be used for fine-grained films because the analysis requires the voltage drop U at each grain boundary to exceed the thermal voltage $U_T \equiv kT/e$. This experimental condition can no longer be met in fine-grained polysilicon samples containing millions of grains in series. Other techniques, such as measurements of the optical absorption[9] or the thermally activated conductance[10] avoid this experimental restriction but yield, on the other hand, only information about the electronic properties of the grain *boundaries*. To the best of our knowledge there exists so far no experimental technique to probe the electronic properties of the *grains* of fine crystalline films.

The present paper reports on noise measurements of polycrystalline silicon films. We show that electrical noise contains information about electrically active traps within the *grains* of the polysilicon. The grain boundaries influence noise only indirectly. They act in a similar way to the Schottky contacts in the case of the classic capacitance spectroscopy techniques for single crystals such as deep-level transient spectroscopy (DLTS),[11] or admittance spectroscopy: The grain boundaries just provide the space-charge region which guarantees the electrical measurability of the traps. The band bending within the space-charge region results in a crossover point of the horizontal Fermi level and the trap energy that runs parallel to the bent band edges.

The noise in our p-type samples is caused by the statistical exchange of holes between the traps and the valence band essentially at the spatial location of the said crossover point. We evaluate the noise spectra with a method which resembles to some extent DLTS;[11] we call therefore our new technique deep-level-noise spectroscopy (DLNS). This analysis yields the energetic position, the capture cross section, as well as the concentration of traps within the grains of our fine-grained polysilicon.

Quantitative investigations of fluctuation phenomena due to generation and recombination processes have successfully been carried out for traps in spatially homogeneous single crystals.[12] Our present investigation differs from this previous work because we make explicit use of the spatial *inhomogeneities* induced by the existence of the crystallographic defects, the interface charge, and the depletion regions around the semiconductor grain boundaries.

II. SAMPLE PREPARATION

Our polysilicon of 0.5 μm thickness is grown at 625 °C by low-pressure chemical-vapor deposition of Si onto oxidized Si wafers with 0.6 nm SiO_2. A mean grain size of 20 nm is measured with a transmission electron microscope.[13] After film deposition, boron or arsenic are implanted as dopants with energies of 40 and 100 keV, respectively, at various implantation doses. The implanted films are annealed at 900 °C for 30 min.

Here we report on detailed noise investigations of p-type samples that were boron implanted with a dose of 9×10^{14} cm^{-2}. From the measured room-temperature Hall constant R_H and the elementary charge q we deduce by Hall effect a free hole density $p = 1\times10^{18}$ cm^{-3} at

room temperature using the relation $p = 1/qR_H$. This p value is an order of magnitude lower than the implanted boron density of 2×10^{19} cm^{-3} which we estimate from the implantation dose and the thickness of the polysilicon. Ohmic contacts are provided by evaporating aluminum, which is subsequently annealed at 500 °C for 10 min.

III. EXPERIMENTAL RESULTS

The noise measurements are performed in a four-terminal configuration where a battery-powered source applies a constant current I_0 to the two outer contacts of four parallel evaporated Al stripes. The voltage fluctuations δU around a mean voltage drop U_0 are measured at the two inner stripes, which have a distance of a few millimeters. We amplify, filter, digitize, and then Fourier transform the fluctuations with the help of an array processor.[14] The square of the Fourier components is proportional to the voltage noise power density $S_U(f)$ at frequency f.

Figure 1 shows noise spectra obtained at various temperatures from our boron-doped sample. We prefer the ordinate $2\pi f S_U(f)$ for the graphical representation of frequency-dependent noise data. Such a plot is better appropriate for the analysis of noise spectra than the usual double-logarithmic delineation. The linear representation is particularly suitable for spectra which deviate only slightly from $1/f$ behavior. Pure $1/f$ noise would be depicted as a horizontal line, thus small deviations from $1/f$ noise are easily distinguished. The linear ordinate yields in addition a sensitive delineation of the noise $S_U(f)$. High experimental resolution of $S_U(f)$, low scatter of the data points, as well as a high resolution on the frequency scale are therefore experimental prerequisites for smooth data curves as a basis for a precise theoretical analysis. We achieve the required high experimental resolution of $S_U(f)$ with the help of 12-bit analog-to-digital converters. The computation speed of our array processor guarantees the real-time computation of power spectra with 1024 points on the frequency axis up to 30 kHz. We obtain, therefore, about 1800 individual noise spectra per minute in this frequency range and are thus able to average a large number of individual spectra within a reasonable time. This averaging of a large number of complete spectra gives us the desired smoothness of the noise while we are still able to maintain a high resolution on the frequency scale.

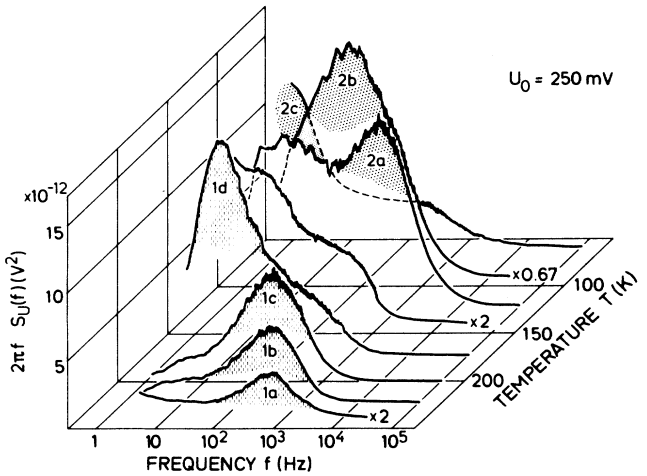

FIG. 1. Noise power density $S_U(f)$ multiplied by frequency $2\pi f$ for an overall mean voltage drop $U_0 = 250$ mV at different temperatures. Maxima shifting with temperature can clearly be discerned as exemplified by the sequences termed $1a-1d$ and $2a-2c$ for two maxima. Maximum 1 corresponds to a trap located 200 meV above the valence-band edge, maximum 2 to a trap at 50 meV.

Our experimental results in Fig. 1 demonstrate that we do not observe a $1/f$ behavior. Instead we detect sharp maxima in each spectrum. The frequency where these distinct maxima occur depends strongly on temperature as shown for two maxima in Fig. 1. The first maximum occurs at 500 Hz at room temperature (curve $1a$) and shifts to 1 Hz at 175 K (curve $1d$). Similar behavior is observed for the second maximum labeled with the sequence $2a-2c$.

Each of the noise spectra in Fig. 1 consists of the superposition of a small (up to about four) number of Lorentz curves with time constants τ_i and amplitudes A_i:

$$S_U(f) = \sum_i \frac{A_i}{1+(2\pi f\tau_i)^2} \ . \tag{1}$$

We use in the following the two main maxima in Fig. 1 and analyze them.

When the time constants τ_i of the superposition of Lorentz curves as in Eq. (1) differ sufficiently, then the overlap of the single Lorentz contributions is small and the maxima in the plot $2\pi S_U(f)$ versus frequency f like in Fig. 1 occur at frequencies f_i where $2\pi f_i\tau_i = 1$ holds. The temperature dependence of the noise spectra in Fig. 1 originates from the temperature dependences of the time constants τ_i.

Our finding of single maxima is in contrast to earlier investigations by other authors[15] who found a $1/f$ dependence for the noise power density. These $1/f$ spectra were interpreted[15] in terms of the phenomenological Hooge model which does not allow physical parameters to be extracted.

The observation of individual sharp maxima in polycrystalline films differs also from our own earlier results obtained from single grain boundaries as well as from coarse-grained polycrystals.[7,16] In these large-grained samples we found under the experimental condition $U \gg U_T$ single broad maxima when we evaluated the experiments in plots like Fig. 1. The broad maxima with a weak temperature dependence were the result of the interaction of holes with interface states and of spatial potential fluctuations within the grain-boundary plane.

In the following, we present a model which provides a quantitative explanation for the measured fluctuation phenomena in polycrystalline thin films. The model is compatible with our earlier results on single grain boundaries.[7]

IV. MODEL AND DISCUSSION

Charge transport in polycrystalline semiconductors is strongly influenced by the presence of grain boundaries.[8] These grain boundaries constitute, if electrically charged, a potential barrier of height ϕ_b for the majority-carrier current j_0, as shown in Fig. 2.[5,6] Fluctuation phenomena, i.e., noise at grain boundaries, will generally arise from capture and emission processes in interface states within the boundary plane or in bulk traps near the boundary. Carrier trapping in interface states, which is here represented by the stochastic current j_i, was earlier observed by us in the noise properties of single grain boundaries and of coarse-grained polycrystalline material.[7,16] We argue in the following that the noise here observed is caused by bulk traps in the *grains* of our silicon films. Capture in such bulk traps at energy E_T within the space-charge regions surrounding the grain boundary is characterized by the stochastic trapping current j_t.

Figure 3 shows that the noise from our polysilicon consists clearly of a superposition of discrete Lorentz spectra. The appearance of discrete Lorentz curves cannot be understood in terms of interface states. Noise produced by trapping in interface states would inevitably result in spectra which are broadened when compared to Lorentz curves. This broadening in frequency is caused by the barrier heights which fluctuate from one grain boundary to the next boundary.[7] The spatial barrier distribution must therefore lead to a spatial distribution of the free-hole concentration p_0 at the site of trapping. The time constants τ for any trapping process depend on p_0 by $\tau_p \sim 1/p_0$, and any spatial barrier fluctuations therefore

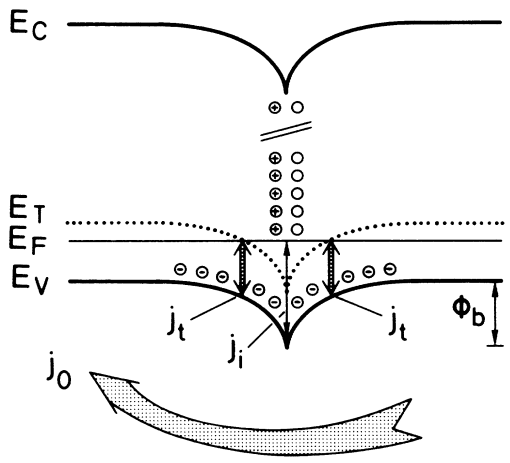

FIG. 2. Band diagram at a grain boundary in a p-type semiconductor. The positive interface charge that results in a potential barrier of height ϕ_b is compensated by negative acceptor ions within the space-charge regions. The noise results from the capture and emission current j_T at traps at energy E_T within the space charge region. The single Lorentz curves like in Fig. 1 cannot be explained by a modulation of the current j_0 by the trapping current j_i in interface states. The Fermi level E_F is flat near the boundary since the voltage drop at a single boundary is negligible.

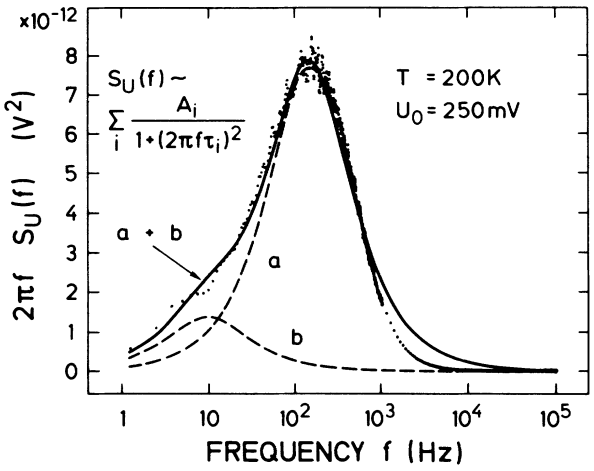

FIG. 3. The product of spectral density $S_U(f)$ and frequency $2\pi f$ for the 200 K spectrum of Fig. 1. Over a wide frequency range, the measured dotted spectrum can be modeled by the sum (solid line) of two dashed Lorentz spectra, *a* and *b*.

inevitably cause a time-constant distribution with a corresponding broadened noise spectrum. Such an observation of spatial potential fluctuations has indeed been possible in bicrystals[7] as well as in polycrystalline samples containing a small number (~ 15) of large grains.[16]

The occurrence of single, Lorentzian-shaped maxima in the noise spectra of Figs. 1 and 2 suggests, therefore, that contributions from capture and emission at interface states are not significant for the noise properties of our thin films. This finding is also understandable within the framework of our earlier model for single-grain boundaries.[7] This model[7] shows that noise from interface states scales with the barrier height ϕ_b. The barrier heights of bicrystal boundaries were earlier[5,7,8] found to be of the order of 300 meV whereas for our polycrystalline films[13] we estimate $\phi_b \approx 20$ meV from conductance measurements. In addition, interface state noise scales with the square of the voltage drop per barrier.[7] In our thin films, with about 10^6 grain boundaries in series, the voltage drop per barrier is in the microvolt region, whereas we had to apply voltages larger than the thermal voltage U_T in order to observe interface noise at single grain boundaries.[7] The smaller grain-boundary barrier height and the smaller voltage drop per barrier explain, therefore, why capture and emission at traps in the grains dominates the noise in our polycrystalline thin films.

Our quantitative description of the noise by capture and emission at bulk traps starts with the well-known Lorentz spectrum $S_U(f)$ that describes trapping noise in a spatially homogeneous p-type semiconductor under the condition that the concentration of trap levels N_T is much smaller than the concentration p_0 of free carriers at the site of trapping:[17]

$$S_U(f) = \frac{U_0^2}{V} \frac{4\tau N_T F_0 (1-F_0)}{p_0^2 [1+(2\pi f \tau)^2]} . \tag{2}$$

Here, F_0 denotes the occupation function of the traps, U_0

the mean voltage drop, and V the volume of the sample. The trapping time constant τ is given by[17]

$$\frac{1}{\tau}=\frac{v_{\rm th}S_p p_0}{F_0}[1+F_0(1-F_0)N_T/p_0]$$

$$\simeq v_{\rm th}S_p N_V\{\exp[-(E_V-E_F)kT]$$

$$+\exp[-(E_V-E_T)/kT]\}\ , \qquad (3)$$

where S_p stands for the capture cross section of the trap at energy E_T, $v_{\rm th}$ for the thermal velocity and N_V for the density of states at the valence band edge. The second part of Eq. (3) holds for $N_T/p_0 \gg 1$.

Generation-recombination spectra described by Eq. (2) have a maximum amplitude near the crossover of the Fermi level E_F with the trap level E_T because $F_0(1-F_0)$ has there a maximum.[18] The potential barriers of the space-charge regions surrounding the grain boundaries ensure a crossover of these two energies even when there exists no crossover point within the single crystalline grains. We expect this crossover to exist even when the space-charge regions from adjacent boundaries overlap.

Due to the sharp maximum of $F_0(1-F_0)$ at the crossover point we take the noise described by Eq. (2) at $E_T=E_F$ where the maximum contribution to the noise occurs:

$$S_U(f)\approx\frac{U_0^2}{V}\frac{\tau^* N_T}{p_0^{*2}[1+(2\pi f\tau^*)^2]}\ , \qquad (4)$$

with the modified time constant τ^*,

$$1/\tau^*=2v_{\rm th}S_p N_V\exp[-(E_V-E_T)/kT]\ . \qquad (5)$$

The quantity p_0^* denotes the density of free holes $p_0^*=N_V\exp[-(E_C-E_T)/kT]$ at the site of trapping. In general, we expect to find trap levels at different energies E_{Ti}. The resulting noise spectrum can then approximately be expressed by the sum of the individual contributions.[19]

V. RESULTS

Figure 3 shows that the overall noise consists indeed of a superposition of very few discrete spectra. Curves *a* and *b* in Fig. 3 are both Lorentzian and are described by Eq. (4). The two curves correspond to two traps below the valence-band edge. The sum of the curves *a* and *b* describes the measured noise over a wide frequency range.

We obtain the information about the energetic location of the traps from the analysis of the temperature-dependent noise. Equation (5) demonstrates that the modified time constant τ^* is thermally activated where the activation energy gives the energetic position E_V-E_T of the traps in the band gap. We therefore measure the temperature dependence of τ^* with the help of the noise at fixed frequencies. Figure 4 shows results for three different frequencies f. The curves are dominated by two maxima which correspond to two discrete trap energies. The temperatures where the maxima occur depend strongly on frequency. According to Eq. (4) we expect the maxima to occur whenever $2\pi f\tau^*=1$ holds, if we neglect the weak temperature dependencies of N_C and $v_{\rm th}$. From the temperature-dependent maxima in Fig. 4 we thus obtain the time constant τ^* as well as its temperature dependence for each trap. This procedure of finding the time constants is similar to the one used in ordinary deep-level transient spectroscopy;[11] we therefore term our analysis deep-level-noise spectroscopy.

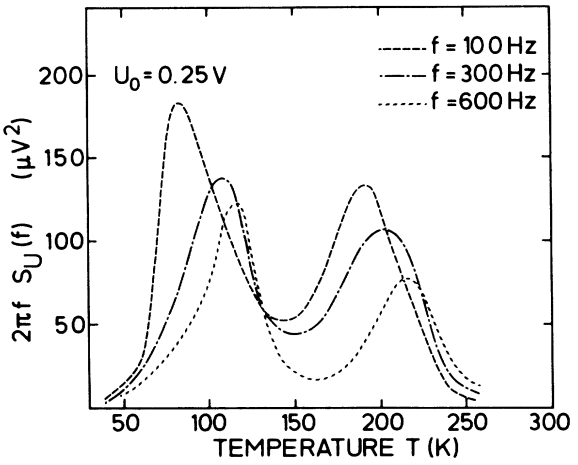

FIG. 4. Noise power density $S_U(f)$ at three fixed frequencies f as function of temperature T. The maxima in this plot originate in two distinct trap levels. The low-temperature maximum corresponds to a trap located 50 meV above the valence band, the high-temperature maximum to a trap at 200 meV.

The Arrhenius plot of the time constants τ^* in Fig. 5 shows the anticipated thermal activation. Values of τ^* obtained from different overall voltage drops fall on the

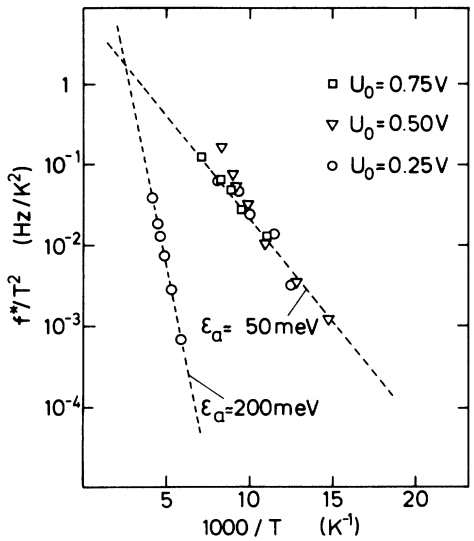

FIG. 5. The Arrhenius plot of the inverse time constant $f^*\equiv 1/2\pi\tau^*$ proves the thermal activation of τ^*. Data obtained at different overall voltage drops fall on the same line. The slopes of the lines give the energetic positions of the traps whereas the intercept with the ordinate yields the capture cross sections.

same line, and demonstrate the consistency of our model. The slopes of the Arrhenius plot yield the respective energy $E_V - E_T$ of the traps within the space-charge region and the intercept with the ordinate determines the capture cross section. We resolve for our boron-doped sample two energy levels at 50 and at 200 meV above the valence-band edge. The capture cross sections are 10^{-19} and 10^{-17} cm^2, respectively.

Once we know the energetic positions of the traps within the band gap, we determine their concentrations. From the condition $2\pi f\tau^* = 1$ for the maxima in Fig. 4, we obtain, with the help of Eq. (4) for the trap density,

$$N_T = \frac{p_0^{*2}}{U_0^2} V [2\pi f S_U(f)]_{\max} , \tag{6}$$

where the subscript max indicates that the value of $2\pi f S_U(f)$ is taken from the maxima in Fig. 4. Using Eq. (7), we find for the 200-meV trap a density of $N_T = 5.7 \times 10^{15}$ cm^{-3} and for the 50-meV trap a density of $N_T = 1.3 \times 10^{18}$ cm^{-3}. The concentration of the 50-meV trap is comparable to the measured Hall carrier concentration. This finding as well as the energy of 50 meV strongly indicate that this trap is just the implanted boron.

VI. CONCLUSION

We have developed noise spectroscopy into a versatile tool for the analysis of electrically active impurities within the grains of polycrystalline thin films. Deep-level-noise spectroscopy seems to be the first method capable of characterizing *bulk* traps in such films. This method is particularly suitable for highly doped polycrystalline silicon. Such highly doped films are most important in the technology of integrated circuits, and it is just their properties that are the least understood. We find that the noise spectra of our films do not show $1/f$-like behavior as found earlier for single grain boundaries[7] but consist of the superposition of a small number of Lorentz spectra. The Lorentz spectra are caused by bulk traps and the thermally activated noise yields the energy, the concentration, as well as the capture cross section of the traps.

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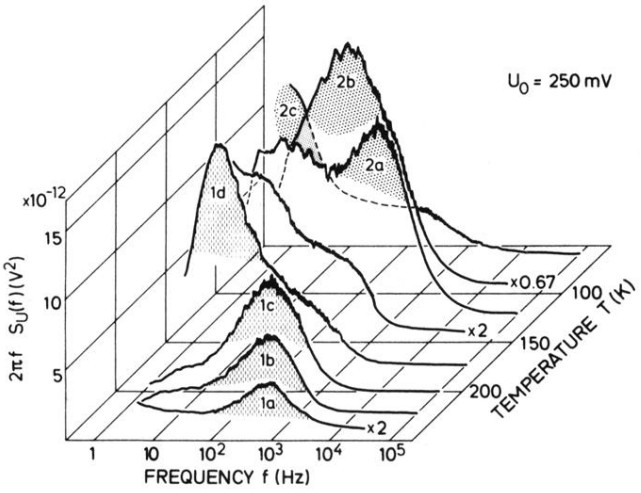

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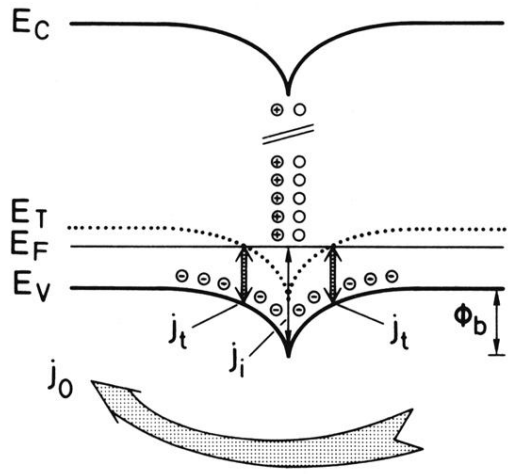

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