1/*f* noise in mono- and polycrystalline aluminum

M. J. C. van den Homberg, A. H. Verbruggen,* P. F. A. Alkemade, and S. Radelaar
DIMES, Faculty of Applied Sciences, Delft University of Technology, P.O. Box 5046, NL-2600 GA Delft, The Netherlands

E. Ochs, K. Armbruster-Dagge, A. Seeger, and H. Stoll
Max-Planck-Institut für Metallforschung, Heisenbergstrasse 1, D-70569 Stuttgart, Germany
(Received 27 June 1997)

The $1/f$ noise in three types of aluminum lines has been investigated in the temperature range 140–510 K. The types are one long single crystal, a chain of short single crystals (''bamboo''), and a polycrystal. In the lines of the first two types the $1/f$ noise power is significantly lower than in the polycrystalline specimens. The temperature dependence of the noise power in the polycrystalline lines shows a plateau between 370 and 415 K, corresponding to activation energies 0.9–1.0 eV. Both types of monocrystalline lines have equal noise power with a peak around 340 K, corresponding to an activation energy of about 0.8 eV. In the polycrystalline lines the dominant contribution to $1/f$ noise appears to be the thermally activated motion of atoms in grain boundaries. The measurements on the monocrystalline lines reveal the existence of at least one further contribution to $1/f$ noise in metals, presumably associated with the thermally activated diffusion of atoms along dislocations. [S0163-1829(98)06601-6]

Resistance fluctuations in continuous metal films exhibit a power spectrum that is approximately inversely proportional to the frequency f. Mobile lattice defects are known to contribute considerably to these resistance fluctuations,[1] e.g., low-temperature irradiation with electrons, by which atomic defects are introduced, increases the $1/f$ noise of metal films drastically.[2,3] Dutta, Dimon, and Horn (DDH) demonstrated that a significant part of the $1/f$ noise in metal films can be attributed to thermally activated processes with activation energies and relaxation times characteristic for atomic diffusion.[4] In measurements of the $1/f$ noise versus temperature for pure Al and for Al with Si and Cu additives, Koch and co-workers found that the additives increased the activation energies.[5] A similar increase in the activation energy upon Si and Cu addition is generally observed for Al electromigration (atomic diffusion) along grain boundaries.[6] These experimental findings strongly indicate that a significant part of the $1/f$ noise in polycrystalline metal films is due to diffusion along grain boundaries. Further support for the prevailing role of grain boundaries stems from the work of Verbruggen and co-workers.[7] In their comparison of several gold samples, the lowest $1/f$ noise intensity was observed in the samples with fewer grain boundaries.

The question arises whether mechanisms not involving grain boundaries or atomic defects contribute to $1/f$ noise in metal films. To answer this question, it is necessary to investigate the relationship between $1/f$ noise and the microstructure of the films. Even though the importance of the microstructure for $1/f$ noise is commonly acknowledged, so far little work has been done to investigate this relationship in detail. It is not trivial to fabricate similar metal lines with totally different microstructures. In this paper we present measurements of the temperature-dependent $1/f$ noise of three types of microstructures with similar geometry and purity: one long single crystal, a chain of short single crystals, and a polycrystal. Henceforth, the chain of single crystals is referred to as a bamboo line.[8] This work provides experimental evidence that also thermal motion of atoms along dislocations causes $1/f$ noise.

All lines, 400 μm long and with similar widths (0.6–0.9 μm) and thicknesses (0.3–0.45 μm), were fabricated in the same sputtering apparatus under the same vacuum conditions. Hence, their impurity contents, which might affect $1/f$ noise,[9] were similar. For the fabrication of the single-crystal and bamboo-structured samples we used guided recrystallization of Al in an SiO_2 groove pattern with submicron dimensions.[10] The lines became single crystals or bamboo-structured depending on whether a temperature gradient was present during recrystallization or not. They were subsequently annealed for 8 h at 500 K. The polycrystalline lines were patterned from nominally 400 nm-thick films by electron-beam lithography and chlorine-based reactive ion etching and were annealed at 673 K for 30 min. The room-temperature resistivity was 2.8 $\mu\Omega$ cm for the single-crystal and bamboo-structured lines and 2.9 $\mu\Omega$ cm for the polycrystalline lines, indicating that the lines were pure. The microstructure of the lines was characterized thoroughly by transmission electron microscopy (TEM) and scanning electron microscopy (SEM), as well as by backscattering Kikuchi diffraction (BKD).[11–13] The last-mentioned technique allows one to determine the crystallographic orientations locally.[14]

Figure 1 depicts TEM micrographs (bright field) of the recrystallized lines. The wavy, dark lines in the single-crystal line [Fig. 1(a)] are due to bending stresses in the sample introduced during thinning by ion milling. BKD measurements revealed that the lines had a gradual crystallographic rotation of 0.05°/μm about an axis perpendicular to their sidewalls.[11] We attributed this rotation—observed over macroscopic distances in many equivalent samples—to the presence of equally oriented dislocations.[12] Figure 1(b) shows a bamboo-structured line, which is in fact a chain of ~ 3 μm-long grains without any polycrystalline segments. TEM on other samples confirmed the complete absence of polycrystalline segments.[13] The polycrystalline lines had an average grain size of 230 nm (Fig. 2). Dislocations were

0163-1829/98/57(1)/53(3)/$15.00 © 1998 The American Physical Society

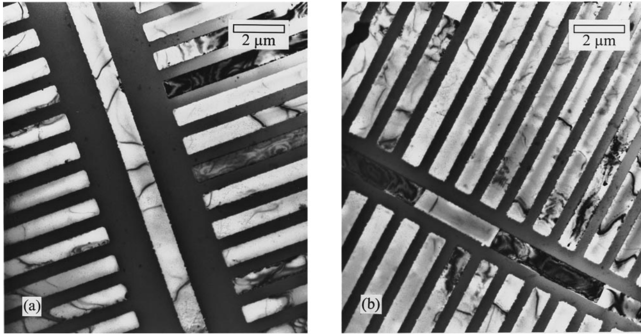

FIG. 1. Planar view TEM micrographs (bright field) of the recrystallized Al samples. The dark areas are the SiO_2 substrate. The long central lines are the test lines. Perpendicular to these lines are dummy side lines. (a) a single-crystal line; (b) a bamboo-structured line with various grains, typically 3 μm long.

observed in all three types of samples; however, no reasonably accurate estimate for their density can be given.

The noise was measured with a phase-sensitive ac-correlation technique, which averages out thermal noise and external interferences.[15] An ac current with a root-mean-square current density on the order of 4×10^{10} A/m^2 was applied to measure the resistance fluctuations. The Joule heating of the samples was less than 6 K. To avoid contributions to the noise spectra by macroscopic temperature fluctuations, the temperature was stabilized to ± 10 mK. At least five samples of each type were measured to ensure accurate and reproducible results. The measured spectral density of the noise power $S_V(f,T)$ is normalized according to[9]

$$S^*(f,T)=\frac{fS_V(f,T)A^3N_a}{lI^2}, \quad (1)$$

where $S^*(f,T)$ is the normalized spectral density of the noise power, f the frequency, T the absolute temperature, A the cross-sectional area of the line, N_a the atomic density of Al (6.02×10^{28} m^{-3}), l the line length, and I the applied current. We note that, if we apply the usual Hooge normalization (i.e., $fS_V(f,T)Al/V^2$, where $V=IR$ is the voltage and R the resistance of the sample),[16] the normalized noise will be trivially temperature-dependent because of the phonon-scattering contribution to the resistance.

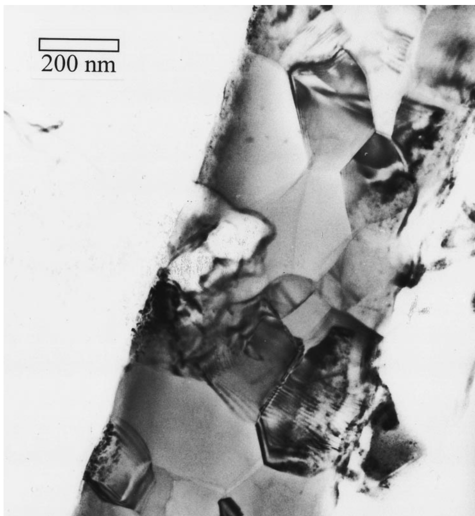

FIG. 2. Planar view TEM micrograph (bright field) of the polycrystalline line. The average grain diameter is 230 nm.

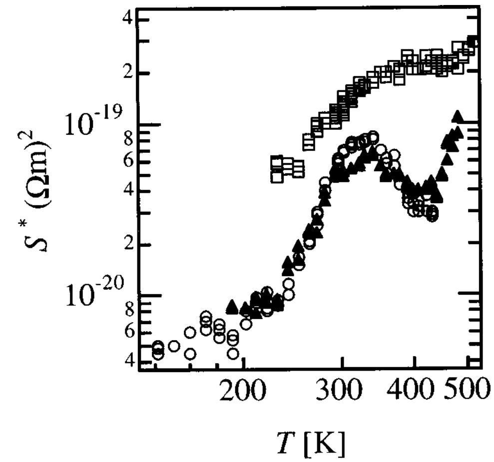

FIG. 3. (a) Temperature dependence of the normalized $1/f$ noise spectral density $S^*(f_0=1\text{ Hz},T)$ for a polycrystalline (□), a bamboo-structured (▲), and a single-crystal (○) Al sample.

Figure 3 shows the normalized $1/f$ noise spectral density $S^*(f,T)$ as a function of temperature. Each point represents the average of the power spectral density of 100 independent time traces. Over the entire temperature range investigated, $S^*(f,T)$ was proportional to $1/f^m$ with m close to 1 (see also Fig. 4). The normalized noise of the bamboo-structured (▲) and single-crystal specimens (○) is much lower than that of the polycrystalline specimens (□) and shows a pronounced maximum at about 340 K. Over the entire temperature range, there is no significant difference in the normalized $1/f$ noise of the bamboo-structured and single-crystal specimens.

The measured temperature dependence of the frequency exponents m of the noise power is in good agreement with the exponents

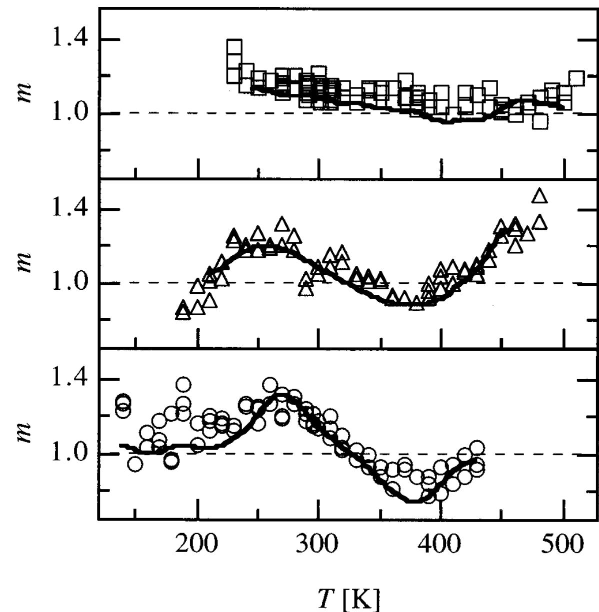

FIG. 4. Experimental frequency exponent m of a polycrystalline (□), a bamboo-structured (△), and a single-crystal line (○). The solid curves give the exponent m derived from the temperature dependence of $S^*(f_0=1\text{ Hz},T)$ according to the model of Dutta, Dimon, and Horn.

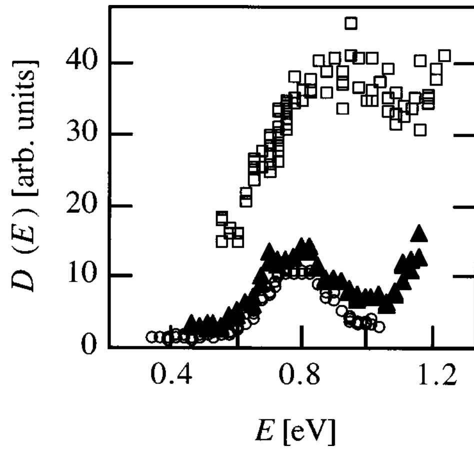

FIG. 5. Distribution function of activation energies, $D(E)$, derived from $S^*(f_0=1\text{ Hz},T)$ according to the model of Dutta, Dimon, and Horn for a polycrystalline (□), a bamboo-structured (▲), and a single-crystal (○) Al sample.

$$m=1-\frac{1}{\ln(2\pi f_0\tau_\infty)}\left\{\frac{d\,\ln[S^*(f_0,T)]}{d\,\ln T}-1\right\}, \quad (2)$$

derived from the temperature dependence of $S^*(f_0,T)$ (at $f_0=1$ Hz) according to the DDH model[4] (Fig. 4). It confirms that the $1/f$ noise in the investigated samples is caused by thermally activated resistance fluctuations. In Eq. (2) τ_∞ is the preexponential factor of the relaxation time of the resistance fluctuations (on the order of the inverse Debye frequency, i.e., 10^{-13} s). Note that the crossover from $m>1$ to $m<1$ occurs near the temperature where $S^*(f_0,T)$ has its maximum, which is in agreement with the DDH model.

In the DDH model, the distribution function of the resistance fluctuations can be inferred directly from the temperature dependence of the noise power according to

$$D(E)\propto\frac{f_0S^*(f_0,T)}{kT}, \quad \text{with } E=-kT\,\ln(2\pi f_0\tau_\infty) \quad (3)$$

(k=Boltzmann's constant). The application of the DDH model to the data of Fig. 3 indicates that the process responsible for the resistance fluctuations in the single-crystal and bamboo-structured samples is characterized by a relatively narrow distribution of activation energies centered around 0.8 eV (Fig. 5). In contrast, the polycrystalline sample has a much broader distribution function with a maximum between 0.9 and 1.0 eV.

The activation energy for the bamboo-structured and single-crystal lines is close to the activation energy of 0.85 eV for pipe diffusion along dislocations as measured by Volin and co-workers.[17] This correspondence and the fact that our samples contain a large number of dislocations, suggest that the $1/f$ noise in the single-crystal and bamboo-structured lines is due to the thermal motion of atoms along dislocations. In the polycrystalline lines the noise associated with grain boundaries dominates. Since the dislocation densities in the specimens are not well known, it is not possible to calculate the relative weights of these two mechanisms. The polycrystalline lines do not show a well-defined activation energy, in agreement with measurements by Kraayeveld and co-workers[18] and by Briggmann and co-workers[3] but in disagreement with the measurements by Koch and co-workers[5] who found a pronounced maximum at 325 K in the noise power of polycrystalline Al.

In conclusion, measurements of samples with very different microstructures have demonstrated that dislocations contribute to $1/f$ noise.

The authors thank M. Kelsch from the MPI für Metallforschung, Stuttgart for the electron-microscopy work and Y. Du for help in preparing the samples. This work was supported by the Technology Foundation (STW), the Netherlands.

*Electronic address: ahv@dimes.tudelft.nl

[1] M. B. Weissman, Rev. Mod. Phys. **60**, 537 (1988).
[2] J. Pelz and J. Clarke, Phys. Rev. Lett. **55**, 738 (1985).
[3] J. Briggmann, K. Dagge, W. Frank, A. Seeger, H. Stoll, and A. H. Verbruggen, Phys. Status Solidi A **146**, 325 (1994).
[4] P. Dutta and P. M. Horn, Rev. Mod. Phys. **53**, 497 (1981).
[5] R. H. Koch, J. R. Lloyd, and J. Cronin, Phys. Rev. Lett. **55**, 2487 (1985).
[6] F. M. d'Heurle and P. S. Ho, in *Thin Films—Interdiffusion and Reactions*, edited by J. M. Poate, K. N. Tu, and J. W. Mayer (Wiley, New York, 1978), Chap. 8.
[7] A. H. Verbruggen, R. H. Koch, and C. P. Umbach, Phys. Rev. B **35**, 5864 (1987).
[8] D. T. Walton, H. J. Frost, and C. V. Thompson, in *Materials Reliability in Microelectronics I*, edited by J. R. Lloyd, F. G. Yost, and P. S. Ho (Materials Research Society, Pittsburgh, 1991), p. 219.
[9] J. H. Scofield, J. V. Mantese, and W. W. Webb, Phys. Rev. B **32**, 736 (1985).
[10] M. J. C. van den Homberg, P. F. A. Alkemade, A. H. Verbruggen, A. G. Dirks, J. L. Hurd, and S. Radelaar, Microelectron. Eng. **35**, 277 (1997).
[11] M. J. C. van den Homberg, A. H. Verbruggen, P. F. A. Alkemade, and S. Radelaar, in *Materials Reliability in Microelectronics VI*, edited by W. F. Filter, J. J. Clement, A. S. Oates, R. Rosenberg, and P. M. Lenahan (Materials Research Society, Pittsburgh, 1996), p. 127.
[12] M. J. C. van den Homberg, P. F. A. Alkemade, S. Radelaar, J. L. Hurd, and A. G. Dirks, Appl. Phys. Lett. **70**, 318 (1997).
[13] M. J. C. van den Homberg, P. F. A. Alkemade, A. H. Verbruggen, A. G. Dirks, E. Ochs, and S. Radelaar, in *Materials Reliability in Microelectronics VII*, edited by J. Clement, R. Keller, K. Krisch, J. Sanchez, and Z. Suo, MRS Symposia Proceedings No. 473 (Materials Research Society, Pittsburgh, in press).
[14] J. A. Venables and C. J. Harland, Philos. Mag. **27**, 1193 (1973).
[15] A. H. Verbruggen, H. Stoll, K. Heeck, and R. H. Koch, Appl. Phys. A: Solids Surf. **48**, 233 (1989).
[16] F. N. Hooge, T. G. M. Kleinpenning, and L. K. J. Vandamme, Rep. Prog. Phys. **44**, 31 (1981).
[17] T. E. Volin, K. H. Lie, and W. Balluffi, Acta Metall. **19**, 263 (1970).
[18] J. R. Kraayeveld, Ph.D. thesis, Delft University of Technology, 1995.