# CREEP BEHAVIOR OF THIN FOIL OF LOW-ALLOYED ALUMINUM FOR MICROELECTRONIC CIRCUIT

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**ABSTRACT** Tensile creep tests on thin sheets of an Al-1mass%Si-0.5mass%Cu alloy for microelectronic circuit lines with thickness ($t$) of 100~50μm have been conducted at 200℃ under constant load with an initial stress ranging from 20 to 50MPa. The fracture and deformation behavior has been characterized as a function of specimen thickness and grain size ($d$). Creep rate was shown to increase with decreasing $t/d$, and to have stress exponent ranging from 7.9 to 10.4 for a fixed $t/d$ value. Slip line was observed on the surface of the tested specimens. Therefore the deformation was concluded to be based on dislocation creep under the tested conditions.

**Keywords**: *aluminum-1mass%silicon-0.5mass%copper alloy, creep, specimen thickness, grain size, dislocation*

## 1.INTRODUCTION

Currently, with the sharp increase in the scale of integration in microelectronic circuits, the dimension of aluminum connect lines in the circuits has been decreased into submicron. Figure 1 illustrates the cross section of an aluminum line together with surrounding materials. For example, aluminum connect lines with width of about 0.3μm and thickness under 0.2μm are being used in a 64 Mbit DRAM (Dynamic Random Access Memory) and, from now on, further sharp increase in the scale is expected. With such refinement in the connect lines, reliability problems, such as what are called electromigration and stress migration, have become marked. Electromigration is a failure phenomenon caused by the transportation of aluminum atoms by high-density electric current (impingement with many electrons) in the line[1], while stress migration can be regarded as a kind of elevated temperature deformation and fracture, which occurs at about 200℃ in spite of no electric current[2]. The cause of stress migration is the remaining tensile stress in the line as high as about 500MPa at 30℃, since the passivation film coating and final sintering treatment are performed at high temperatures ranging from 300 to 450℃ and there is a large difference in thermal expansion coefficient between the aluminum line and the surrounding materials[3]. The failure of stress migration takes place at grain boundaries and has been thought to be induced by diffusional creep[1-3]. However, experimental results that support it, such that creep rate is in simple proportion to stress and in inverse proportion to the square or cube of grain size[4], have not been obtained yet. Diffusional creep is one of the deformation mechanisms but does not describe the fracture mechanism. Moreover, in bulk aluminum base materials, neither difussional creep nor intergranular fracture has been known to occur at about 200℃. Although there is a possibility that the deformation mechanism changes into diffusional creep when the material thickness is reduced to thin line, no detailed report has been found on the deformation of thin materials at elevated temperatures.

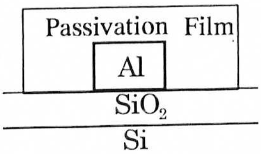

Fig.1 Schematic of the cross section of an aluminum connect line and surrounding materials.

In this study, to elucidate the discrepancy in the deformation and failure mechanism between connect line and bulk, creep behavior has been investigated on thin sheets of 100~50μm thickness of an Al-1%Si-0.5%Cu alloy, which is widely used for connect lines, as a function of specimen thickness and grain size. The fracture mechanism has been also investigated by scanning electron microscope (SEM) observation on the fracture surfaces after the tests. Although the actual line is reported to be under a multi-axial tensile stress condition, as a first step, the tests in this study have been carried out under a uni-axial tensile stress condition.

## 2.EXPERIMENTAL PROCEDURE

Although the actual connect lines are usually produced by sputtering, rolled materials were used in this study. An Al-0.95mass%Si-0.46mass%Cu alloy with impurity iron of 0.01mass% was melted and cast in air using raw materials with purity higher than 99.99%. The ingot was scalped, hot-rolled from 15mm to 2mm in thickness at 400℃, annealed at 400℃ for 30min, cold-rolled to 0.2mm in thickness, annealed at 400℃ for 30min and finally cold-rolled into sheets with thickness of 50, 70 and 100μm. In order to increase the grain size at a fixed specimen thickness, some of the sheets were annealed at 400℃ for 30min before the final pass of the cold-rolling. Tensile test pieces with gage length of 10mm and width of 6mm were machined from the sheets and annealed at 450℃ for 1h. This annealing corresponds to the sintering heat treatment performed in the final manufacturing process of microelectronic circuits[2].

Creep tests were conducted in tension in air at 200℃ under constant load with initial stresses ranging from 20 to 50MPa. The change in the gage length was measured by photographing the gage intermittently and observing the negatives with an optical microscope. After the tests fracture surface and free surface of the specimens were observed with a JSM-5400 SEM.

## 3.EXPERIMENTAL RESULTS AND DISCCUSION

The results in this paper will be shown primarily for an initial stress of 35MPa. Figure 2 shows creep curves of three specimens prepared without the annealing for grain coarsening. The broken lines were obtained by applying least square method to steady-state region. Steady-state creep rate (slope of the line) increases with the decrease in specimen thickness. Creep curves of the specimens with larger grain size (solid symbols) are shown in Fig.3 for the thickness of 70 and 100μm along with those of normally prepared specimens (open symbols; already shown in Fig.2). The increase in the grain size is found to enhance the creep deformation. Figure 4 shows dependence of steady-state creep rate on grain size. Creep rate roughly tends to increase with grain size corresponding to Fig.3, although insensitive to grain size when $t/d>1$, i.e., grain size is smaller than

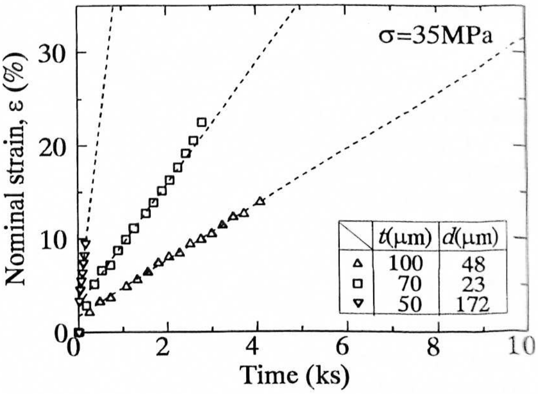

Fig.2 Creep curves at 200℃ at an initial stress (σ) of 35MPa.
$t$: specimen thickness,
$d$: grain size in longitudinal direction.

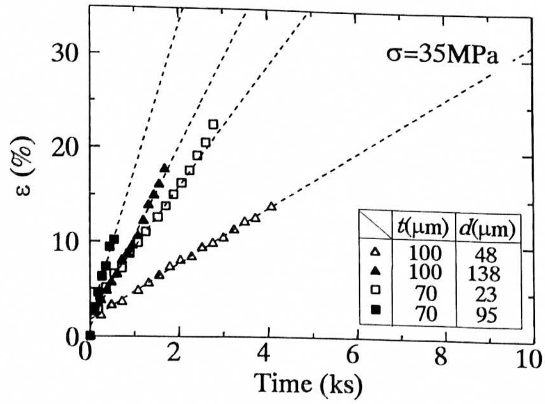

Fig.3 Creep curves of the specimens with different grain size.

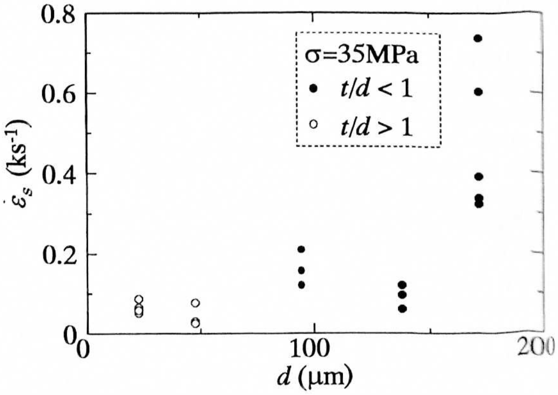

Fig.4 Dependence of steady-state creep rate ($\dot{\varepsilon}_s$) on $d$.

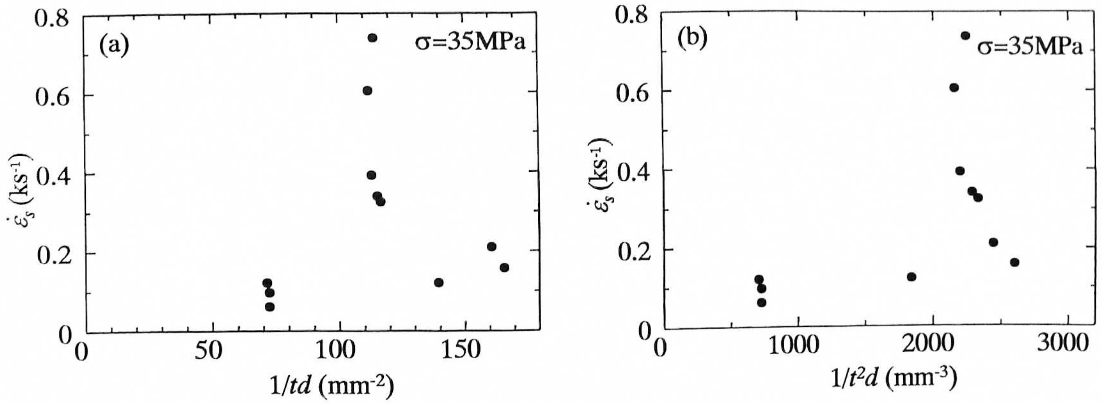

Fig.5 Dependence of $\dot{\varepsilon}_s$ on $1/td$ and $1/t^2d$ when $t/d<1$. (a) $\dot{\varepsilon}_s$ vs. $1/td$, (b) $\dot{\varepsilon}_s$ vs. $1/t^2d$.

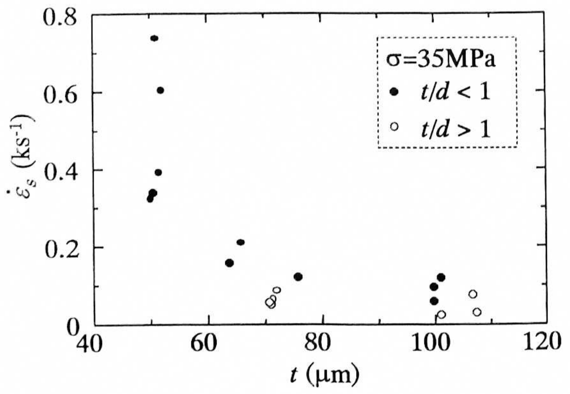

Fig.6 Dependence of $\dot{\varepsilon}_s$ on $t$.

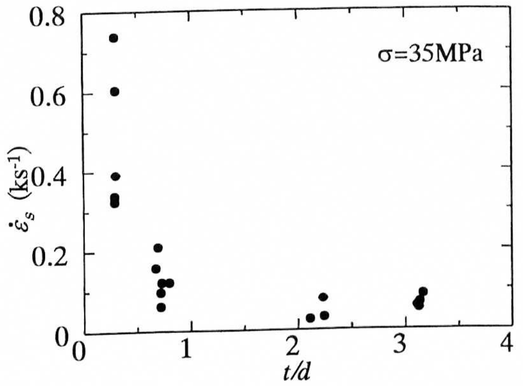

Fig.7 Relationship between $\dot{\varepsilon}_s$ and $t/d$.

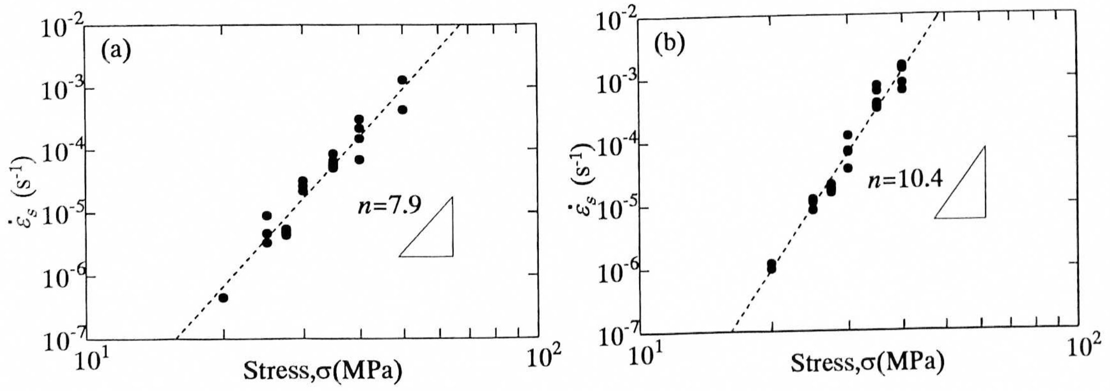

Fig.8 Double logarithmic plots of $\dot{\varepsilon}_s$ with σ. (a): $t$=70μm, $d$=31μm; (b): $t$=50μm, $d$=172μm.

specimen thickness. This feature is obviously different from that expected from diffusional creep where creep rate should be in inverse proportion to $d^2$ or $d^3$ when $t/d>1$. When $t/d<1$, creep rate is expected to be proportional to $1/td$ or $1/t^2d$. Figure 5 (a) and (b) shows the change in the creep rate as a function of $1/td$ and $1/t^2d$, respectively. It is evident that the creep rate does not change in proportion either to $1/td$ or to $1/t^2d$ [5].

Dependence of steady-state creep rate on specimen thickness is shown in Fig.6. Although steady-state creep rate seems to increase with decreasing specimen thickness, it varies with grain size at the same thickness, as mentioned above. The relationship between steady-state creep rate and $t/d$ is plotted in Fig.7. It is found that steady-state creep rate increases with decreasing $t/d$, and it is obvious that this tendency is marked when $t/d<1$. Comparing Fig.7 with Fig.4 or Fig.6, $\dot{\varepsilon}_s$ vs. $t/d$ plot is found to have a closer correlation than $\dot{\varepsilon}_s$ vs. $t$ or $\dot{\varepsilon}_s$ vs. $d$ plot.

In addition to the results of σ=35MPa, creep rates were measured at other stress levels and Fig.8 shows double logarithmic plots of stress vs. creep rate for specimens with fixed $t$ and $d$ values. From this graph, the creep rate is shown to follow the power law

$$\dot{\varepsilon}_s \propto \sigma^n , \qquad (1)$$

with the stress exponent $n$ (slope of the plot; broken line) of 7.9 in Fig.8 (a) and 10.4 in Fig.8 (b). The stress exponents of other specimens varied but all of them were in the range from 7.9 to 10.4. These values were far greater than that ($n$=1) expected from the diffusional creep. In the previous paper by the authors, silicon phase particles were found to be sparsely dispersed in the specimens, which have been also used in this paper. Although creep data should be analyzed using threshold stress in such alloys with second phase particles, results with apparent $n$ values over 7 have been frequently reported when the dislocation creep is the operating mechanism and the data are analyzed according to Eq.1 without using threshold stress[6].

An example of the fracture surface appearance after the tests is shown in Fig.9. It was

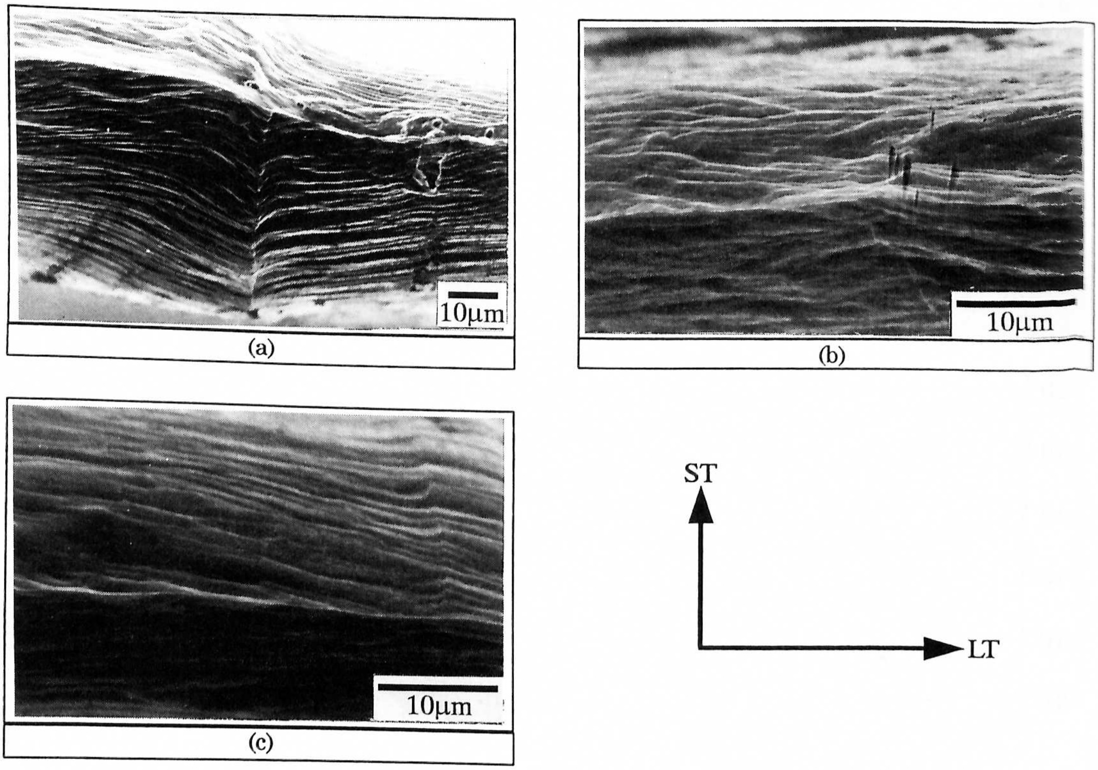

Fig.9 SEM micrographs of the fracture surfaces. (a) $t$=70μm, $d$=184μm, σ=40MPa; (b) $t$=50μm, $d$=117μm, σ=30MPa; (c) $t$=50μm, $d$=117μm, σ=25MPa.

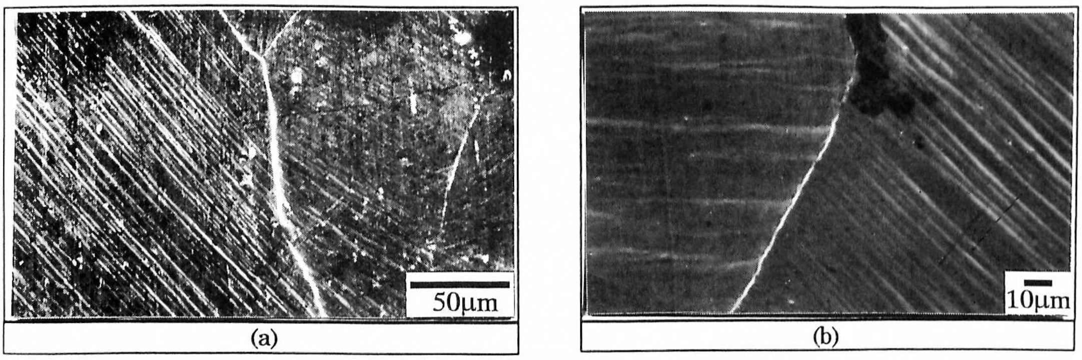

Fig.10 SEM micrographs of the specimen surface after the tests. (a) $t$=70μm, $d$=184μm, σ=40MPa; (b) $t$=100μm, $d$=161μm, σ=30MPa.

found that all of the specimens failed in fully transgranular manner with a fracture surface of chisel line pattern which is shown in the figure and is characteristic of extremely ductile fracture. This is different from the typical fracture of stress migration (intergranular fracture), showing that deformation behavior in the present experiment should be also different from that in stress migration. Another interesting feature in Fig.9 is a set of step lines running in the width (LT) direction on the specimen surface (not on the fracture surface). Surface morphology of tested specimens is shown in Fig.10, where a number of slip lines are observed irrespective of grain size. Hence the step lines shown in Fig.9 are also deduced to be slip lines, and it can be concluded that the operating deformation mechanism in the present study is dislocation creep. As shown in Fig.10, slip lines became indistinct when the stress level decreased. This can be attributed to the longer time to fracture at the lower stress, which allow surface diffusion to smoothen the surface steps.

## 4.SUMMARY

In this study, creep behavior has been investigated on thin foils with 100~50μm thickness of an Al-1%Si-0.5%Cu alloy as a function of specimen thickness and grain size. It was found that creep rate increased with decreasing $t/d$; dependence on grain size was completely different from that expected from diffusional creep. The stress exponent $n$ ranged from 7.9 to 10.4 and was also evidently larger than the value of unity expected from diffusional creep. Furthermore, slip lines were observed on the surface of tested specimens. Therefore, the deformation was concluded to be based on not diffusional creep but dislocation creep under the tested conditions. However, all of the specimens fractured in transgranular manner with a chisel line pattern, implying that the deformation and fracture behavior in the actual connect lines were not represented in the range of the present experimental conditions. They might be represented in the test by further decreasing the specimen thickness as well as the grain size, by using the specimens prepared by sputtering, or by applying multi-axial stress to the specimen.

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