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Electromigration Reliability of the Contact Hole in SiC Power Devices Operated at Higher Junction Temperatures

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Abstract. It is strongly desired to operate SiC power devices at higher junction temperatures (T_j), but that often entails problems because they contain a variety of materials with thermal activity or weakness. An example of such troubles is the steep increase in resistance of the Al electrode in the source (or emitter) contact holes, caused by electromigration (EM). In this work, EM reliability of the contact hole in SiC power devices was evaluated for an improved Al electrode sandwiched between thin TaN layers. An estimated mean time to failure (*MTTF*) of approximately 3400 years was achieved under conditions of T_j = 300°C and $J = 10^4$ A/cm^2.

Introduction

There has always been an overwhelming need for drastically reducing the volume, weight and cost of the power electronics components used in consumer products and automobiles. A promising solution that meets this need is the use of SiC power devices at higher junction temperatures (T_j), resulting in a dramatic reduction of the heat-sink apparatus [1, 2]. However, since these devices are actually constructed of not only SiC but also a variety of materials with thermal activity or weakness, higher T_j operation is often problematic and requires adequate measures against potential failure [3]. An example of such problems is the steep increase in Al electrode resistance caused by electromigration (EM). This principally happens in source (or emitter) contact holes where the load current is concentrated.

In our previous work [3], a TaN film was shown to be very effective in SiC power MOS devices as a barrier against adverse interactions between the Al electrode and underlying materials such as Ni_2Si source contacts, the poly-Si gate electrode and the interlayer dielectric. This paper presents an evaluation of the EM reliability of an Al electrode sandwiched between two thin TaN layers. The upper TaN layer functions to prevent EM while the lower TaN layer serves as an interaction barrier. Experimental results show that such electrodes are sufficiently reliable in contact holes even when high current density is applied at high T_j. The preliminary results were reported elsewhere [4].

Experimental

Since the EM failure described above tends to occur mainly in power devices with Al electrodes deposited in the contact holes on the source, a cross-bridge Kelvin resistance test structure as shown in Fig. 1 was used as the test samples. In this structure, the upper Al electrode, sandwiched between 150-nm-thick sputtered TaN layers, is connected to the lower single Al electrode through a via-hole (A = 2.3×2.3 μm^2) opened in the interlayer dielectric (ILD) made of 1-μm-thick silicate glass chemically vapor-deposited with SiH_4 and O_2 at atmospheric pressure. Ta films 50 nm in thickness were additionally put on the outside of the TaN layers in order to maintain consistency with our previous efforts [3]. Both Al electrodes contained 1 wt% Si and their thickness was 2 μm and 1 μm for the upper and lower one, respectively. Samples were fabricated on thermally oxidized (100) Si

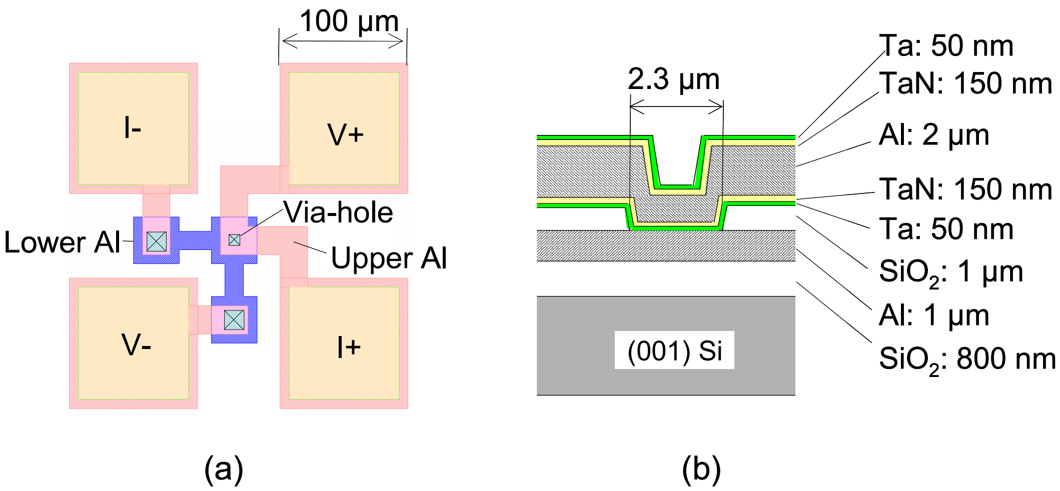

Fig. 1 Sample structure: (a) plan view and (b) cross-section of via-hole

substrates using the standard Si LSI (large-scale-integration) process with double-level Al metallization and then mounted in ceramic packages after being diced.

Various levels of constant direct-current stress, *I*, were applied to the via-hole Al electrode, and the change in its electrical resistance, *R(t)* (= *V(t)*/*I*), was constantly monitored at different T_j using a 4-wire remote sensing technique. The current flow direction was from the upper to the lower Al electrode and the current flowed *across* the lower TaN layer. The density of current stress, *J*, was defined as the current value divided by the sectional area of the via-hole, *I*/A (A/cm^2). Figure 2 shows the typical change in the resistance of a sample where R_0 was the starting resistance. It is seen that the resistance, *R*, steeply increased after a certain period of elapsed time. Such a steep increase, of course, results from EM for the upper Al electrode in the via-hole. In this paper, the EM lifetime (= time to failure, t_F) is defined as the time when *R* rose by 1%. A minimum of three samples were tested for one combination of *J* and T_j and then their mean time to failure (*MTTF*) was determined. As a typical example, when $J = 1.4\times10^6$ A/cm^2 and T_j = 300°C, t_F values of 3.18×10^4 s, 4.14×10^4 s and 4.21×10^4 s were recorded for three test samples, resulting in an *MTTF* of 3.84×10^4 s with a standard deviation of $\sigma_n = 5.7\times10^3$ s.

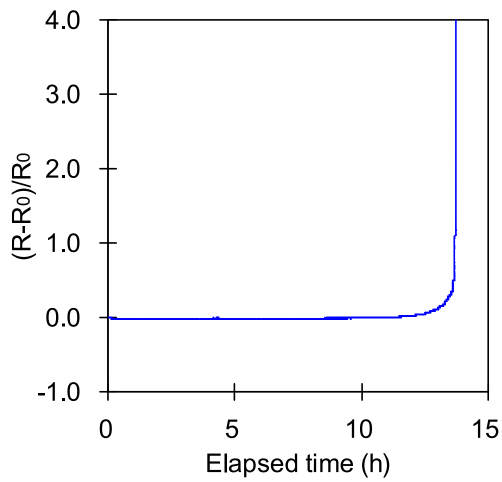

Fig. 2 Typical change in electrical resistance (*R*) of a test sample when $J = 1.4\times10^6$ A/cm^2 was applied at T_j = 300°C. R_0 is the starting value of *R*.

Results and Discussion

The results of EM tests performed on the samples are shown in Fig. 3 where the *MTTF* values for four T_j levels are double-logarithmically plotted as a function of *J*. *MTTF* is well expressed as a decreasing power function of *J*, $MTTF = K\cdot J^{-n}$, where K is an arbitrary constant. The power numbers determined by regression approximation ranged from n = 3.0 to 3.4, as noted in the figure, and were clearly higher than the theoretical value (n = 2) derived by Black using a simple one-dimensional model [5]. This discrepancy may be attributed to the complicated 3-dimensional configuration of the conductors, Al and TaN, in the via-hole of the samples (see Figs. 1 and 5).

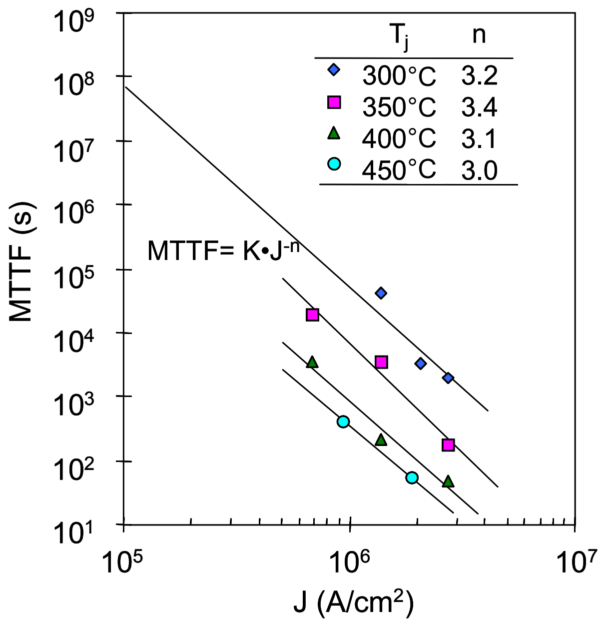

Fig. 3 Mean time to failure (*MTTF*) as a function of current stress (*J*) at various T_j.

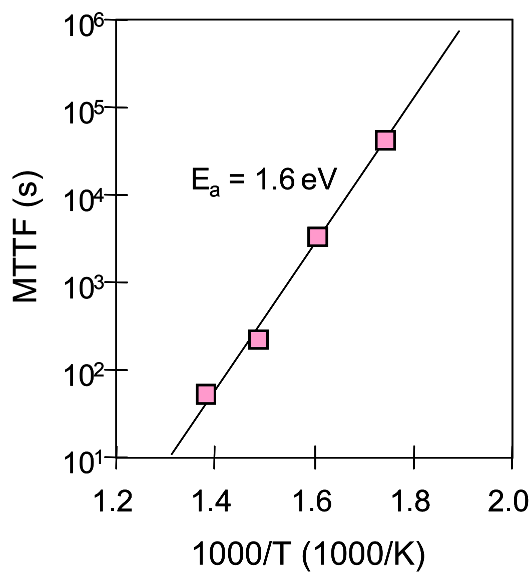

Fig. 4 Arrhenius plots of *MTTF* for $J = 1.4\times10^6$ A/cm^2. E_a is the activation energy obtained with a linear least-square method.

Today, the load current density of SiC power switching devices is, at most, < 300 A/cm^2 [5, 6]. However, it may well be that future devices will reach a level as high as 1000 A/cm^2. It is estimated that the current density in the contact holes of future devices may reach approximately 10^4 A/cm^2, assuming that the ratio of contact to the entire cell area is 1:10. Extrapolating the results in Fig. 3 to $J = 10^4$ A/cm^2 leads to an MTTF of about 3400 years at $T_j = 300$°C. This estimation, although containing some degree of experimental error, suggests that our Al electrode with TaN on both sides will be applicable even to future devices with much higher current density.

Figure 3 also indicates that the *MTTF* of the tested samples decreases steeply with T_j. The *MTTF* at $J = 1.4\times10^6$ A/cm^2 in this figure is plotted as a function of $1/T_j$ (1/K) in Fig. 4. We see that the change in the *MTTF* can be described with an Arrhenius equation. Using a linear least-squares method, the activation energy was estimated to be $E_a \sim 1.6$ eV. This E_a value is clearly higher than the data previously reported for EM failure of ordinary Al electrodes formed laterally on Si substrates [7-9]. This difference may also be the result of the peculiar configuration of the samples.

The scanning ion micrograph in Fig. 5 displays the cross-section of the via-hole in a failed

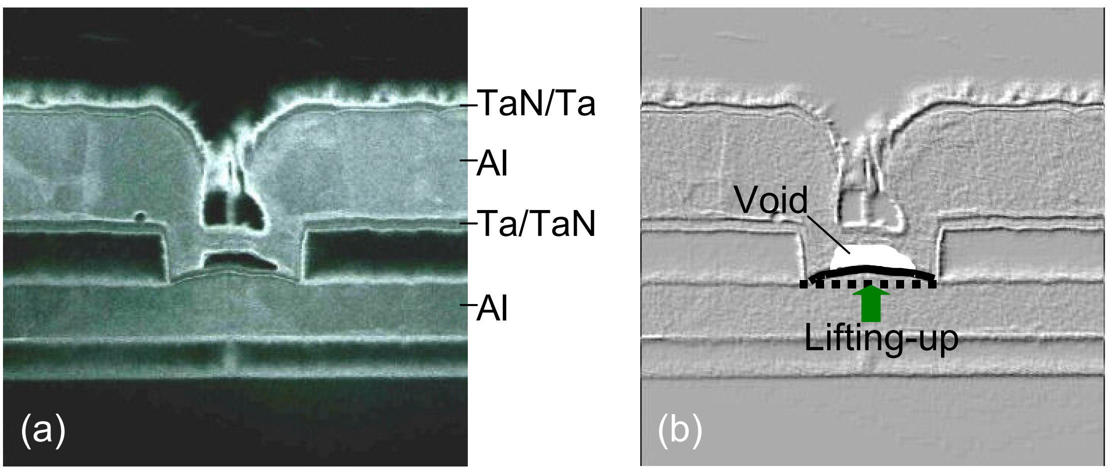

Fig. 5 A cross-section of a failed sample in which resistance increased by 70%: (a) scanning ion micrograph and (b) embossed image. The incident angle of the ion beam is 60°.

sample in which electrical resistance increased by 70%. There are two distinct indications of EM failure: (1) a large void over the bottom TaN layer and (2) the lifting-up of this layer. The void was produced by massive movement of Al atoms in the upper electrode at the bottom of via-hole, resulting in a rapid increase in the via-hole resistance, as shown in Fig. 2. The lifting-up of the layer is the result of EM in the lower single Al electrode used for experimental convenience. It does not contribute to the rise in the via-hole resistance and hence has no relation to the results indicated in Figs. 3 and 4.

Summary

Electromigration reliability of the contact hole in SiC power devices was evaluated for an improved Al electrode sandwiched between thin TaN layers. The electrode demonstrated long-term reliability even at higher junction temperatures. An estimated *MTTF* of approximately 3400 years was achieved under conditions of T_j = 300°C and $J = 10^4$ A/cm^2. The results indicated that the *MTTF* of the tested samples followed the Black-like equation [6, 7],

$$MTTF = K \cdot J^{-n} \exp(qE_a/k_B T_j),$$

where n = 3.0-3.4, E_a = 1.6 eV, q =1.60×10^{-19} C and $k_B = 1.38\times10^{-23}$ J·K^{-1} as the electron charge and the Boltzmann constant, respectively, and K is an arbitrary constant.

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