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A Study on the Electromigration Characteristics in Ag, Cu, Au, Al Thin Films

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Recent ULSI and multilevel structure trends in microelectronic devices minimize the line width down to less than 0.25㎛, which results in high current densities in thin film interconnections. Under high current densities, an EM(electromigration) induced failure becomes one of the critical problems in a microelectronic device. This study is to improve thin film interconnection materials by investigating the EM characteristics in Ag, Cu, Au, and Al thin films, etc.

EM resistance characteristics of Ag, Cu, Au, and Al thin films with high electrical conductivities were investigated by measuring the activation energies from the TTF (Time-to-Failure) analysis. Optical microscope and XPS (X-ray photoelectron spectroscopy) analysis were used for the failure analysis in thin films.

Cu thin films showed relatively high activation energy for the electromigration. Thus Cu thin films may be potentially good candidate for the next choice of advanced thin film interconnection materials where high current density and good EM resitance are required. Passivated Al thin films showed the increased MTF(Mean-time-to-Failure) values, that is, the increased EM resistance characteristics due to the dielectric passivation effects at the interface between the dielectric overlayer and the thin film interconnection materials.

Keywords : Electromigration, Thin film interconnection, Mean lifetime, Activation energy

I. Introduction

In a recent microelectronic device, the failures by the EM induced mass transport are of considerable interest specially in Al-alloy thin film interconnections having widths down to less than 0.25㎛ [1-5]. Because of the small dimensions of microelectronic devices, very high current densities (of the order of 10^6 A/㎠) are common in thin film interconnections, as compared to 10^4 A/㎠ in bulk samples. They cause the gradual formation of voids/hillocks at high current densities resulting in electrical opens/shorts in the circuit interconnections, respectively. The connecting thin film interconnections in the integrated circuits failed after short lifetimes because voids developed due to an electromigration. An appreciable amount of electromigration can be observed in thin films already at ambient temperatures.

The electromigration phenomenon was at first believed to be due to coulombic interactions between the moving ion and the electric field. However, later on it was observed that the electromigration induced mass transport occurred in a direction opposite to that expected from electrostatic ion-field interactions [6-7]. It was known that electromigration is caused by scattering of the moving electrons with the ions, i.e., by momentum transfer between electrons and ions. This electron-ion interaction is sometimes referred to as "electron wind."

Many investigations have been conducted

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with the main purpose to increase the life time of thin film interconnections. Most studies were directed towards the determination of the lifetime of thin film interconnections as a function of current density, composition, geometry and temperature, etc. Various types of experiments such as measurement of the MTF(Mean-Time-to-Failure), direct observation of hole and hillock formation by electron microscopy, the concentration profile of solute elements by microprobe analysis, resistometric techniques, have been developed for electromigration studies. Several factors such as geometry [8-9], current conditions [8-11], line dimensions [12-13], passivations [14-15], material selection [16-17] and microstructures [18-20], etc. are generally known to influence on the electromigration characteristics in thin film interconnections of a microelectronic device. Dielectric passivations have been reported to reduce the EM induced mass transport specially in Al alloy thin film interconnections. The general agreement of the results on the passivation effects is that the MTF is proportional to the passivation thickness [14].

The purpose of this study is to improve the thin film interconnection materials by investigating the electromigration characteristics including the activation energies for the EM of Ag, Al, Au, and Cu thin films, etc.

II. Experiment

Ag, Al, Au, and Cu thin films with the thickness of 0.05 ㎛, the width of 100 ㎛, and the length of 5000 ㎛ were evaporated onto the thermally grown 500 ㎚ SiO_2 layer on p-type Si(100) substrates. EM resistance characteristics of Ag, Al, Au, and Cu thin films with high electrical conductivities were investigated by measuring the activation energies from the TTF (Time-to-Failure) analysis. MTF was calculated from the TTF values which were taken at the current stressing time to electrically open state. Activation energies(Q) were calculated by the following equations [21-22].

$$MTF = Aj^{-n} \exp(Q/kT)$$

Temperatures from a room temperature to 240℃ were utilized for an accelerated EM test. Current densities of $2x10^6$ A/㎠ - $6x10^6$ A/㎠ were applied for the EM test. Optical microscope and XPS (X-ray photoelectron spectroscopy) analysis were used for the failure analysis in thin films.

III. Results and Discussion

Fig. 1 shows the typical resistance change ratio(%) versus direct current stressing time of Cu thin film interconnections. In this study, the TTF values were determined at the current stressing time to electrically open state. Similar resistance changes were also observed in Al, Ag, Au thin film interconnections, etc. Fig. 2a and 2b show the typical resistance change ratio(%) versus direct current stressing time of nonpassivated- and SiO_2 passivated Al-1%Si thin film interconnections with 400 ㎛ length, respectively. The SiO_2 passivated Al-1%Si interconnections shows longer TTF value than the nonpassivated interconnection.

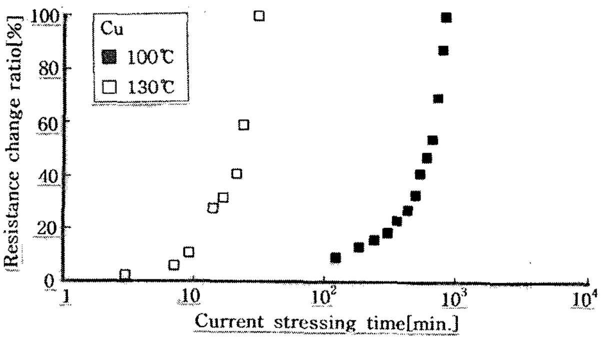
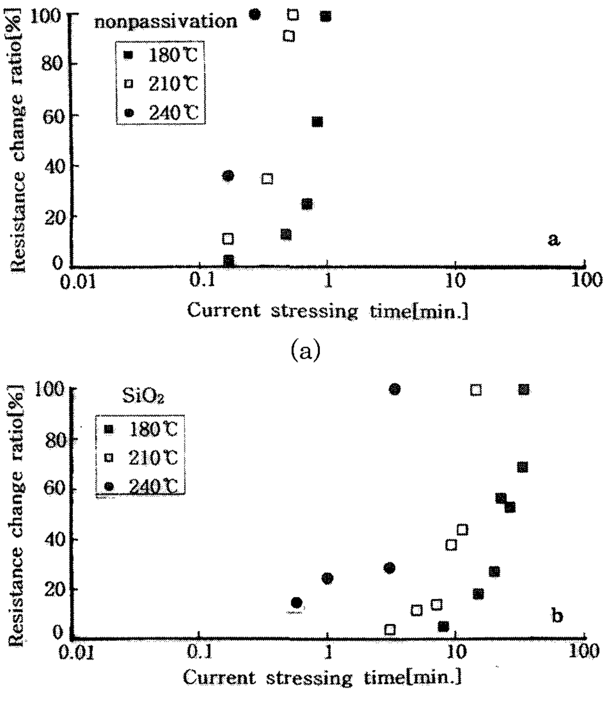


Fig. 1. Resistance Change Ratio(%) vs. Current Stressing Time(min.) of Cu at $j=2x10^6$ A/㎠



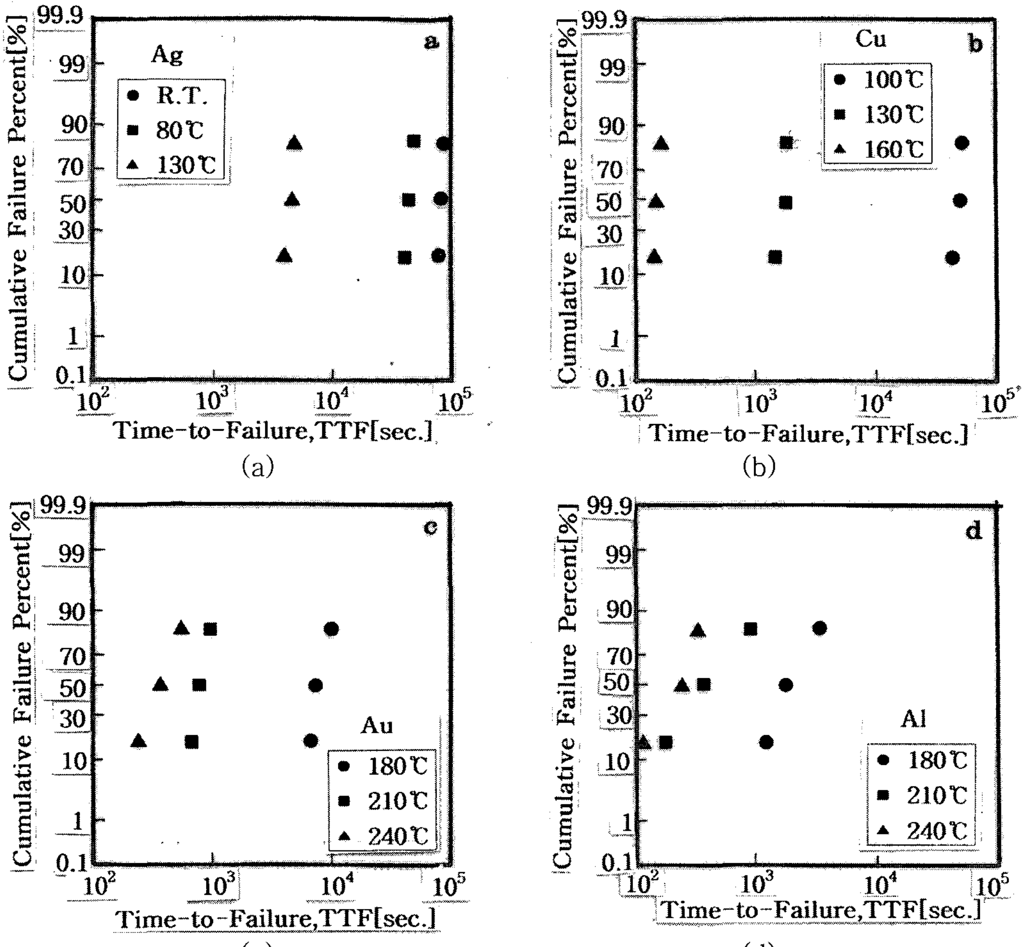
(a)

(b)

Fig. 2. Resistance Change Ratio(%) vs. Current Stressing Time(min.) of (a) nonpassivated- and (b) SiO$_2$ passivated Al-1%Si interconnections with 400 ㎛ length at j=4.5 x10^6 A/㎠

Fig. 3 shows the TTF versus cumulative failure percent of Ag, Cu (at a current density of 2x10^6 A/㎠), and Au, Al (at a current density of 6x10^6 A/㎠) thin film interconnections. Compared with Ag and Cu thin films, Au and Al thin films showed much longer TTF values at the same current density of 2x10^6 A/㎠. Thus a higher current density of 6x10^6 A/㎠ was utilized for an accelerated EM test in Au and Al thin films. Similarly, higher temperatures were also applied for an accelerated EM test in Au and Al thin films than in Ag and Cu thin films. It is expected that Al and Au thin films will show much longer MTF values than Ag and Cu thin films under the same EM test conditions. Mean-Time-to-Failure (MTF, t_{50}) values of Ag, Cu, Au, and Al thin film interconnections are shown in table 1. Fig. 4 shows the TTF versus cumulative failure percent of nonpassivated-, and SiO$_2$ passivated-, 400㎛ long Al-1%Si thin film interconnections at a current density of 4.5x10^6 A/㎠. At temperatures of 180 ℃, 210 ℃, and 240 ℃, the MTFs of nonpassivation were decreased 60 s(σ = 0.42), 26 s(σ= 0.45), 16 s(σ= 0.54), the MTFs of SiO$_2$ passivation were decreased 1753 s(σ= 0.29), 902 s(σ= 1.16), 241 s(σ= 0.78). The SiO$_2$ passivated Al-1%Si thin film interconnections showed the longer MTF value, that is, the better characteristics on electromigration than nonpassivation. The increase of the MTF by SiO$_2$ passivation in Al alloy interconnections has been reported in the literature[8-9]. In comparision with nonpassivated films, passivated thin films showed the increased MTF values, that is, the decreased EM induced mass transport due to the dielectric passivation effects at the interface between the dielectric overlayer and the Al-1%Si interconnection. Fig. 5 also shows the TTF versus cumulative failure percent of 800㎛ long Al-1%Si thin film interconnections stressed at a current density of 4.5x10^6 A/㎠. At temperatures of 180 ℃, 210 ℃, and 240 ℃, the MTFs of nonpassivation were again decreased 49 s(σ= 0.35), 32 s(σ= 0.53), 15 s(σ= 0.32), the MTFs of SiO$_2$ passivation were decreased 1058 s(σ= 0.52), 550 s(σ= 0.55), 205 s(σ= 1.04). The same passivation effects on the MTF are also observed in case of 800㎛ long Al-1%Si thin film interconnections as described. As in 400㎛ long Al-1%Si interconnections, SiO$_2$ passivated Al-1%Si thin film interconnections showed the longer MTF value, that is, the better electromigration resistance characteristics than nonpassivation.

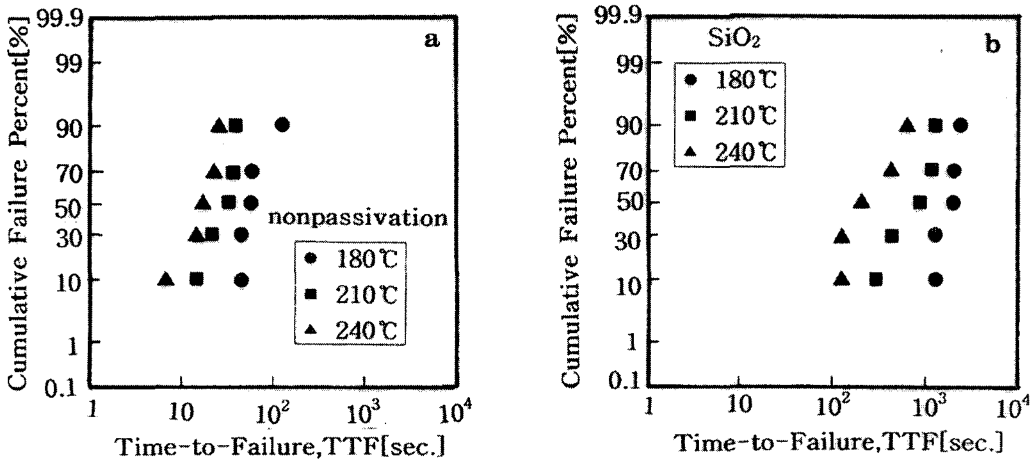
Activation energies for electromigration of pure Ag, Cu, Au, and Al thin films are shown in Fig. 6. Activation energies were calculated by taking Arrhenius plot of the Black equation MTF = $Aj^{-n}\exp(Q/kT)$ from the measured MTF values and temperatures. The calculated activation energies were 0.30 eV, 0.71 eV, 1.01 eV, and 1.33 eV for the case of Ag, Al, Au,



(a) (b)

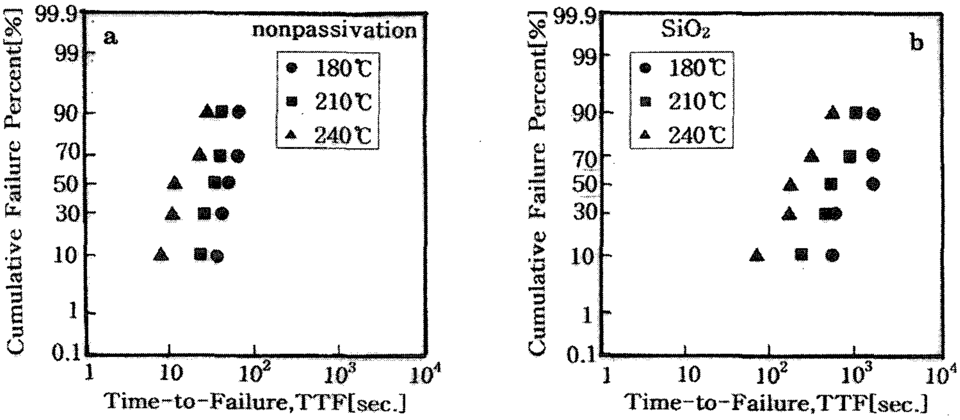
(c) (d)

Fig. 3. (a) Time-to Failure(TTF) vs. cumulative failure percent(%) of Ag at R.T., 80 ℃, and 130 ℃. (j=2x10^6 A/㎠), (b) Time-to Failure(TTF) vs. cumulative failure percent(%) of Cu at 100 ℃, 130 ℃, and 160 ℃. (j=2x10^6 A/㎠), (c) Time-to Failure(TTF) vs. cumulative failure percent(%) of Au at 180 ℃, 210 ℃, and 240 ℃. (j=6x10^6 A/㎠), (d) Time-to Failure(TTF) vs. cumulative failure percent(%) of Al at 180 ℃, 210 ℃, and 240 ℃. (j=6x10^6 A/㎠)



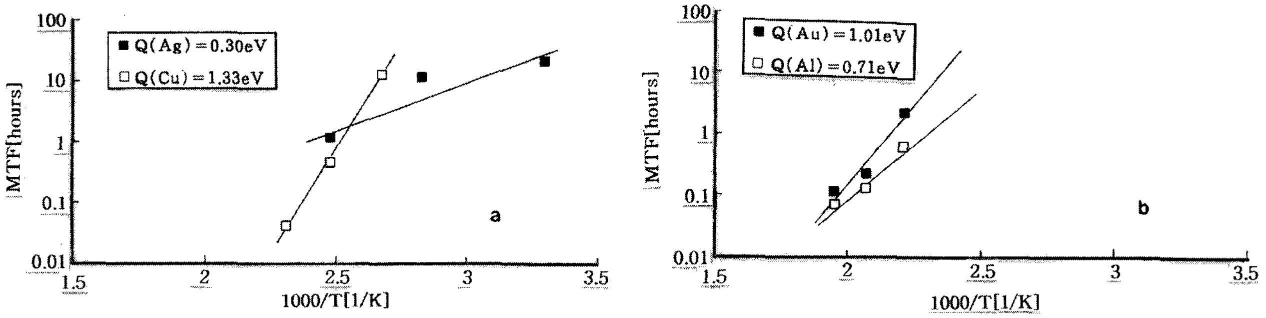
(a) (b)

Fig. 4. Time-to Failure(TTF) vs. cumulative failure percent(%) of (a) nonpassivated- and (b) SiO2 passivated Al-1%Si interconnections with 400 ㎛ length at j=4.5x106 A/㎠



(a) (b)

Fig. 5. Time-to Failure(TTF) vs. cumulative failure percent(%) of (a) non-passivated- and (b) SiO_2 passivated Al-1%Si interconnections with 800 ㎛ length at $j=4.5\times10^6$ A/㎠



(a) (b)

Fig. 6. (a) Activation Energy, Q, of Ag and Cu Calculated from MTF = $Aj^{-n}\exp(-Q/kT)$ (b) Activation Energy, Q, of Au and Al Calculated from MTF = $Aj^{-n}\exp(-Q/kT)$

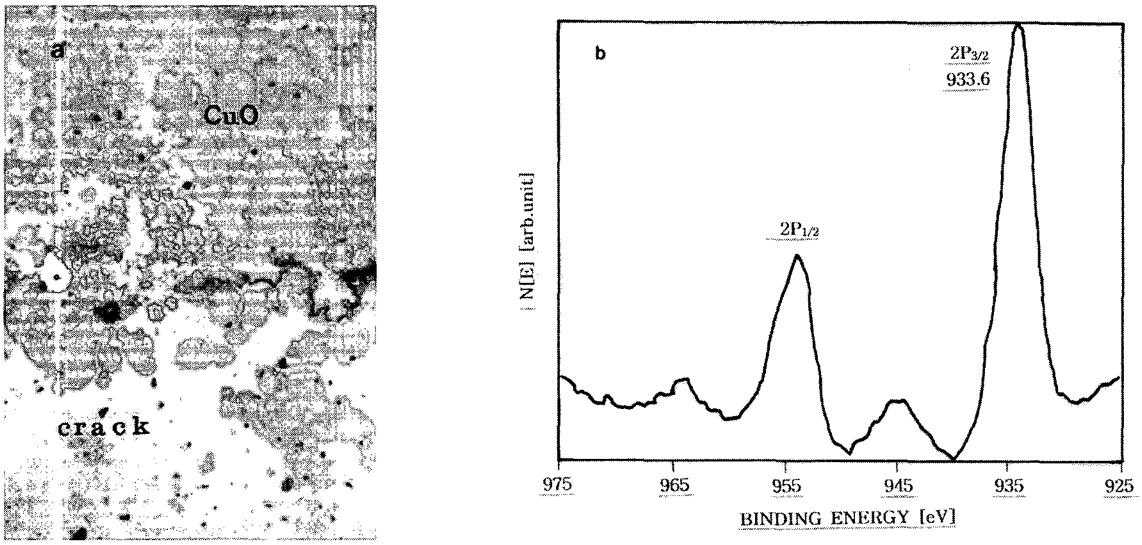


Fig. 7. (a) Optical micrograph and (b) XPS spectrum taken from the Cu thin films after electromigration induced cracks(voids) formed.

and Cu, respectively. In this study, pure metal films without dielectric passivation overlayers were used for comparison. Thus there may be other factors such as surface oxidation, etc. For example, the copper oxide was really observed on the surface of Cu thin films after an EM test.

Fig. 7a and 7b show an optical micrograph and an XPS spectrum, respectively, taken from the Cu thin films after EM induced failures(voids) formed. Cu $2P_{3/2}$ at 933.6 eV and the energy separation of 20.0 eV between Cu $2P_{3/2}$ and $2P_{1/2}$ peak show the CuO formed on top of the Cu films. Neglecting these environmental factors, however, the activation energies of pure Cu, Au films for EM were appeared to be relatively high as 1.33 eV and 1.01 eV, respectively. The activation energies of pure Al and Ag films were measured at relatively low values of 0.71 eV and 0.30 eV, respectively. Au and Cu films seem to have relatively higher resistance for EM than Al and Ag films. Thus Au and Cu films may potentially good candidate for the next choice of advanced interconnection materials where high current density and good EM resistance are required.

IV. Summary

The experimental data on the electromigration characteristics in Ag, Cu, Au, Al thin films with high electrical conductivities lead to the following conclusions: (1) Au and Cu films show relatively high activation energy for electromigration. (2) The calculated activation energies for electromigration were 1.33 eV, 1.01 eV, 0.71 eV, and 0.30 eV for the Cu, Au, Al, and Ag thin films, respectively. (3) Passivation influences on the electromigration characteristics. Al-1%Si thin films with SiO_2 passivation show better EM resistance characteristics than nonpassivation. (4) Pure Cu thin films form CuO on top during operation.

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Ag, Cu, Au, Al 박막에서 엘렉트로마이그레이션 특성에 관한 연구

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최근 미세전자 소자에서 초고집적, 적층구조 추세는 선폭이 0.25㎛ 이하까지 소형화되고 있는 실정이다. 이러한 미세화는 박막배선에서 높은 전류밀도를 초래하게 된다. 높은 전류밀도 하에서는 엘렉트로마이그레이션에 의한 결함발생이 미세전자 소자에서의 치명적인 문제점의 하나로 대두되고 있다. 본 연구는 Ag, Cu, Au, 그리고 Al 박막 등에서 엘렉트로마이그레이션 특성을 조사함으로써 박막배선 재료를 개선하기 위한 것이다.

고전기전도도를 갖고 있는 Ag, Cu, Au, 그리고 Al 박막배선에서 엘렉트로마이그레이션에 대한 저항 특성을 결함발생 시간 분석으로부터 활성화 에너지를 측정함으로써 조사하였다. 광학현미경 그리고 XPS 분석이 박막에서의 결함분석에 사용되었다.

Cu 박막이 엘렉트로마이그레이션에 대해 상대적으로 높은 활성화 에너지를 보였다. 따라서 Cu 박막이 높은 전류밀도 하에서 엘렉트로마이그레이션에 대한 높은 저항성이 요구되는 차세대 미세전자 소자에서 적합한 박막배선 재료로서의 가능성을 갖는 것으로 판단된다. 보호막 처리된 Al 박막은 평균수명 증가, 엘렉트로마이그레이션에 대한 저항 특성 향상을 나타내며 이는 보호막 층과 박막배선 재료 계면에서의 유전 보호막 효과에 기인하는 것으로 사료된다.

주제어 : 엘렉트로마이그레이션, 박막배선, 평균수명, 활성화 에너지

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