The effect of polyimide passivation on the electromigration of Cu multilayer interconnections

JIANN-SHAN JIANG, BI-SHIOU CHIOU
Department of Electronics Engineering and Institute of Electronics, National Chiao Tung University, Hsinchu, Taiwan

Electromigration damage (EMD) is one of the major causes for the failures of interconnect. In this study, the electromigration (EM) of Cu multilayer (TiWN/Cu/TiWN) with polyimide passivation is investigated with an isothermal resistance change method. The EM measurements were carried out on a wafer level at various temperatures (170–230 °C) and current densities (2.28–4.0 MA/cm^2). The activation energy for passivated Cu multilayer is larger than that of the unpassivated ones. The lifetime of passivated specimens are from two to 16 times those of the unpassivated ones. Resistance oscillation, which is attributed to the formation and closing of Cu gap, is observed during EM test. The TiWN interlayer helps to maintain the electrical continuity when a local Cu gap is formed. Hence, the lifetime of Cu metallization is further enhanced by the presence of the interlayer. Copper multilayer interconnect has better EMD resistance than Cu monolayer interconnect does.
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Introduction

With the shrinking in dimensions of VLSI circuits, there is a need for faster performance and higher circuit density. Interconnection RC time delay and current density in the metallization increase as the devices are scaled down [1]. Copper has been considered as a substitute for Al interconnect in VLSI devices, due to its low resistivity, high melting point, high mechanical strength, and better electromigration (EM) resistance [2–5]. However, the deficiencies of copper, such as poor adhesion to the dielectric layers, uncontrollable dry etching, lack of self-passivation oxide and environmental reactivity, limit the usefulness of Cu in IC fabrications. Previous investigations suggest that the EM in copper proceeds via a surface/interface diffusion path [4, 5]. A passivation layer would eliminate the interfacial diffusion or produce an interface that is slower pathway than that typically observed with Cu alone.

This is a continuing research. Previous work indicates that polyimide passivation enhances the lifetime of the Cu metallization. The lifetime of passivated copper films are from 1.1 to 29 times those of the unpassivated ones, depending on passivation materials and current stressing conditions [6]. However, the adhesion strength between Cu and polyimide is poor [6]. Besides, to incorporate Cu into VLSI structure, it is necessary to include diffusion barrier layers to prevent Cu from penetrating into the underlying devices.

A previous investigation [7] also employed a Cu multilayer (TiWN/Cu/TiWN) interconnect on polyimide coated Si substrate. It was found that the underlayer TiWN blocks the diffusion of Cu into polyimide and retards the degradation of the polymer dielectric. Cu multilayer structure proved to be adequate in both preventing Cu from diffusing into the underlying devices and promoting the adhesion strength between Cu and the dielectric layer.

In this research, polymide passivation is applied on the Cu multilayer (TiWN/Cu/TiWN) interconnects fabricated on polyimide coated Si substrate. The isothermal resistance as a function of time is measured and the time to open-circuit failure is employed to evaluate the electromigration damage (EMD) of Cu multilayer. The objective of this study is to enhance the EM resistance of Cu metallization with a multilayer structure and polyimide passivation.

Details of experimental procedures

The preparations of Cu multilayer on polyimide coated Si substrates were described in previous works [6, 7]. After the fabrication of Cu multilayer specimens, polyimide 2540 (Pyralin®, Du Pont, USA) or Polyimide 2610, polyamic acid, was statically dispensed and spun on Cu multilayer with a conventional spin coater (Spinner, Synrex, Taiwan). The spinning process consisted of two steps. The first step, known as dispense-and-spread cycle, is 20 s at 1000 rpm. The second step which determines polyimide films thickness is 30 s at 4500 and 2000 rpm for polyimide PI2540 (P25) and PI2610 (P26), respectively.

Curing (completely imidized) of polyimide was carried out in a quartz tube with nitrogen ambient to prevent the polyimide from degradation. The nitrogen flow rate was 1416 standard centimeter cubic per minute (sccm, i.e., 3 cubic ft/h). The curing profile was given
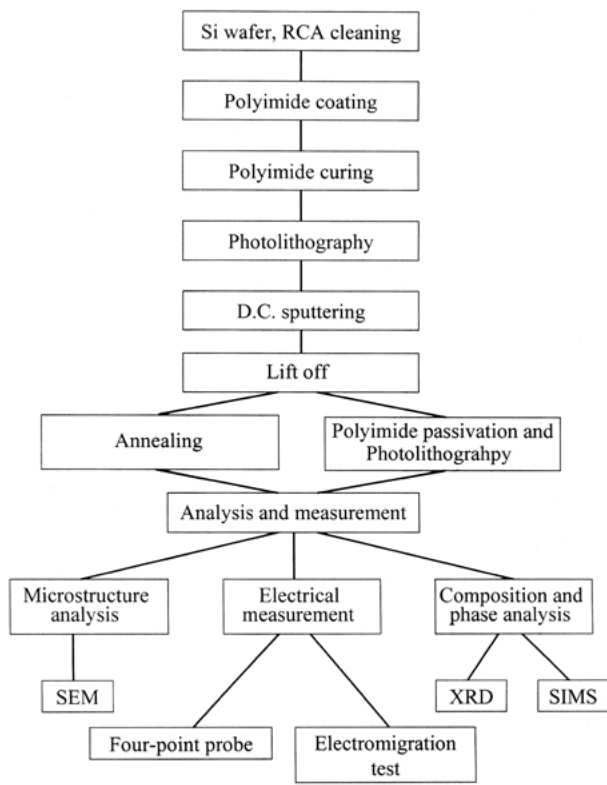
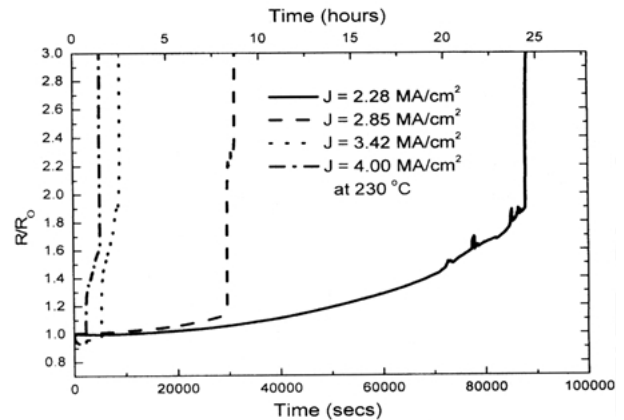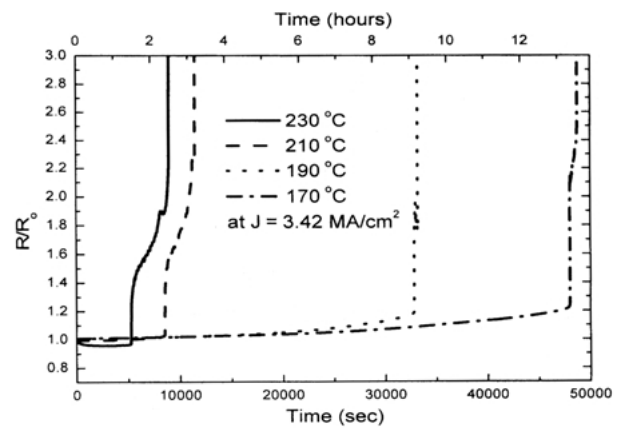Figure 1 Flow chart of the experimental procedures.

Figure 2 Relative resistance as a function of current stress time for P25/TiWN/Cu/TiWN/P25/Si.

Figure 3 Relative resistance as a function of current stress time for P26/TiWN/Cu/TiWN/P26/Si.

previously [5]. The film thickness of the cured polyimide is $\sim 3\,\mu\mathrm{m}$.

The polyimide-coated sample was then proceeded with the conventional photolithography process to obtain the test pattern. The flow chart of the experimental procedures is given in Fig. 1.

The EM tests were carried out in a quartz tube at temperatures ranging from 110 to 230 °C in N_2 atmosphere. The four I/O pads of the samples were connected to a constant current source (Model 220, Keithley, USA) and a micro-voltage meter (Model 197, Keithley, USA). The leads between the samples and measurement system were covered with aluminum foil as an electro-magnetic shielding to avoid the external electro-magnetic interference. The voltage was acquired once per minute or per 10 min automatically. The resistance was obtained by dividing the voltage by the current.

Results and discussion

The kinetics of EMD for Cu multilayer with different passivation is studied with an isothermal resistance change analysis method. Figs 2 and 3 exhibit the typical relative resistance R/R_0 as a function of current stressed time for P25/TiWN/Cu/TiWN/P25/Si and P26/TiWN/Cu/TiWN/P26/Si, respectively. An initial decrease followed by an increase of the resistance is observed, especially for Cu multilayer passivated with polyimide 2540 (P25). Previous works suggest that the depletion of the impurities in Cu grains, which decreases the contribution of solute scattering to resistivity, is one possibility that causes the decrease in resistance [6, 8, 9]. Also seen in Figs 2 and 3 and manifested in Fig. 4 is the oscillation in the resistance of Cu multilayer structure. The resistance oscillation phenomenon was reported

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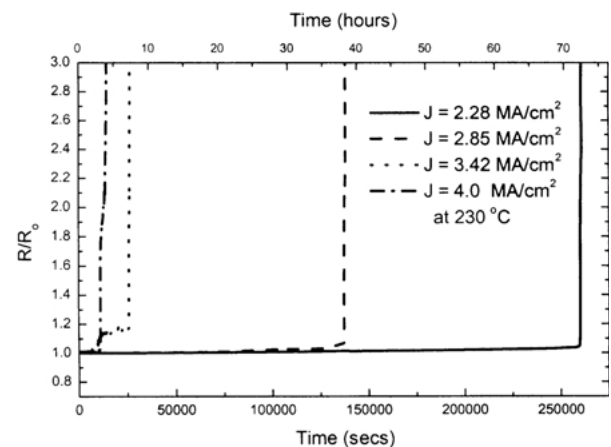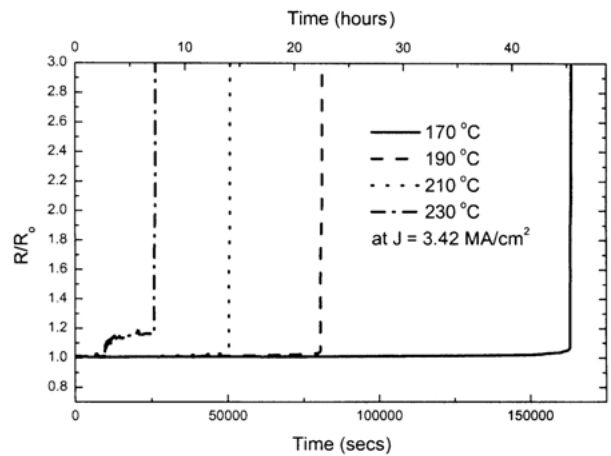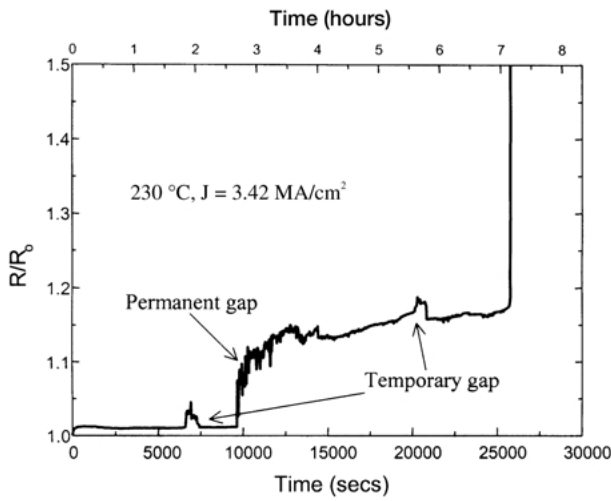*Figure 4* Relative resistance versus current stress time for P26/TiWN/Cu/TiWN/P26/Si. The oscillation in the resistance of Cu multilayer is obvious.

previously in TiN/Al-alloy/TiN multilayer interconnects [10]. It was argued that in the initial stage of EM, resistance increased very slowly with time, signifying small void formation. Then some of small voids coalesced into a ''fatal void'', which finally caused a local Al gap to form, signified by a resistance jump. After a certain time, the resistance jumped back, signifying the Al gap closing or damage healing [10]. The gap formation in the metal layer is one possibility which causes the resistance oscillation in this study. As shown

schematically in Fig. 5, after a local Cu gap is formed, current passes through the TiWN barrier layer next to the gap. As the resistivity of TiWN ($412 \pm 11 \, \mu\Omega\,cm$) is much larger than that of Cu ($1.97 \pm 0.05 \, \mu\Omega\,cm$), the resistance of the interconnect jumps. After a certain time, the resistance jumps back, signifying the Cu gap closing or damage healing. As the stress process goes on, permanent gaps will be formed. The small voids formation was characterized by the increase in the resistance background. It is believed that the driving force for self-healing is the stress gradient induced by metal EM [10]. The electrical force causes a compressive stress σ^+ in the Cu on the left-hand side of the gap, as shown in Fig. 5(a). This stress pushes Cu to fill the gap, causing the resistance to oscillate with time.

The activation energy for EM of copper multilayer can be obtained from the isothermal resistance curves. By defining a resistance change of 4.5% as the criterion of early stage failure, i.e., assuming the dimensions of the maximum voids are much less than the line width, the time rate change of electric resistance (dR/dt) due to EMD is thermally activated and can be expressed by the following empirical equation [7, 11–14]:

$$\frac{dR}{dt} \cdot \frac{1}{R_0} = AJ^n \exp\left(-\frac{Q}{kT}\right) \qquad (1)$$

where R_0 is the initial resistance at a given temperature, A is a pre-exponential factor, J^n is the electron current density raised to the nth power, T is temperature and Q is
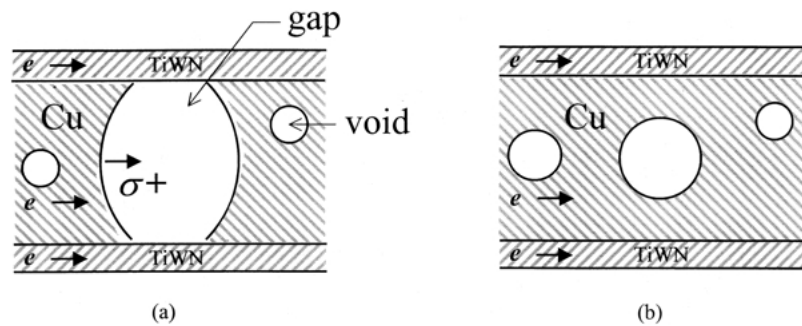

Figure 5 Schmatic diagram of (a) gap formation and (b) gap closing in Cu layer.

T A B L E I Summary of activation energy Q, current exponent n and testing conditions for the electromigration of copper multilayer interconnect

| Interconnect structure	Specimen geometry (µm) L × W × T	Passivation	Testing method and ambient	Q (eV)	n	Reference
TiWN/Cu/TiWN/PI2610	1000 × 7 × 0.27	Polyimide	Resistance, N₂	0.80 eV from 170 to 230 °C at 3.42 MA/cm²	3.07	This work
TiWN/Cu/TiWN/PI2540	1000 × 7 × 0.27	None	Resistance, N₂	0.33 eV from 170 to 230 °C at 3.42 MA/cm²	3.07	[7]
TiWN/Cu/TiWN/PI2610	1000 × 7 × 0.27	None	Resistance, N₂	0.27 eV from 170 to 230 °C at 3.42 MA/cm²	3.07	[7]
Ta/Cu/Ta/PI	300 × 2 × 0.3	Polyimide	Resistance, N.A.*	0.7 eV from 269 to 395 °C at 1.5 MA/cm²	1.1 ± 0.2	[12]
Ta/Cu/Ta/PI	300 × 2 × 1	Polyimide	MTF†, 500 Torr He	1.1 eV from 200 to 395 °C at 2 MA/cm²	N.A.	[17]
TiWN/Cu/TiWN/SiO₂	470 × 0.7 × 0.29	SiO₂	MTF, air	0.97 eV from 238 to 335 °C at 24 MA/cm²	N.A.	[18]

* Not available.
† Mean time to failure.
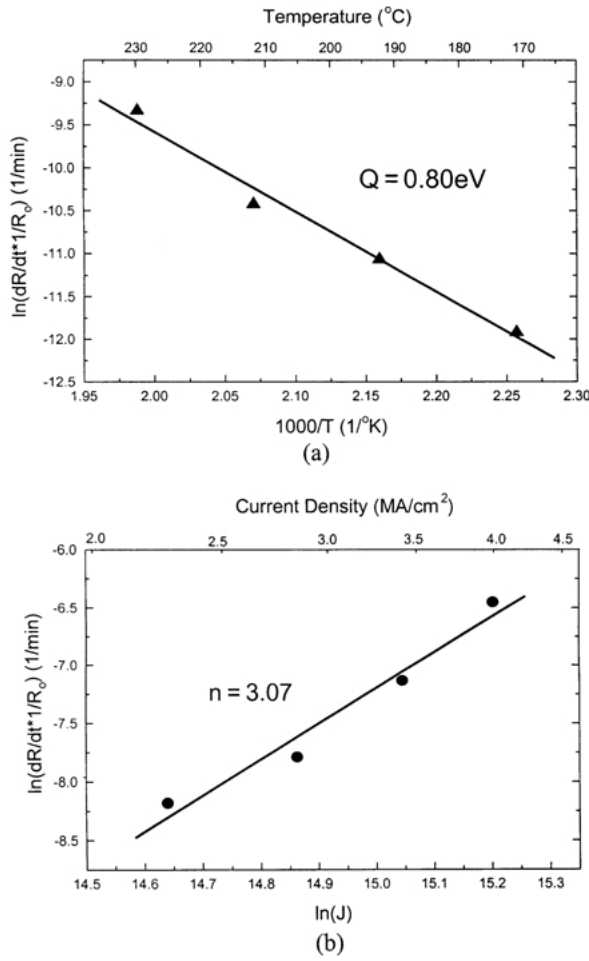
Figure 6 (a) $\ln(dR/dt * 1/R_0)$ versus $1/T$ for P26/TiWN/Cu/TiWN/P26/Si during EMD test, current density: 3.42 MA/cm² and (b) $\ln(dR/dt * 1/R_0)$ versus $\ln(J)$ for P26/TiWN/Cu/TiWN/P26/Si during EMD test. Test temperature: 230 °C. Samples annealed at 420 °C for 30 min. before EMD test.

the activation energy for EM. The activation energy Q and the current exponent n are obtained from the

$$\ln\left(\frac{dR}{dt} \cdot \frac{1}{R_0}\right) \text{ vs } \frac{1}{T} \text{ (for } Q\text{)}$$

and

$$\ln\left(\frac{dR}{dt} \cdot \frac{1}{R_0}\right) \text{ vs } \ln J \text{ (for } n\text{)}$$

plots as shown in Fig. 6 for polyimide passivated Cu multilayer (P26/TiWN/Cu/TiWN/P26/Si). The passivated Cu multilayer has larger activation energy than the unpassivated ones, as summarized in Table I. The current exponent n is ~ 3.07 for the multilayer structure in this study. A current exponent of 2 has been obtained by solving a relatively simple diffusion equation where mass transport due to both a concentration gradient and an EM force are treated concurrently [15]. Values of n greater than 2 can probably be attributed to Joule heating effects which results in a temperature gradient-induced flux divergence [16].

Table II summarizes the failure time ratio among samples with various passivation. Passivation increases sample life time and Cu multilayer passivated with PI2610 has longer lifetime than those with PI2540, as shown in Table II. Previous work suggests that the rigidity of the passivation is the controlling factor for EM resistance [6]. The Young's modulus of PI2610 and PI2540 are 1050 and 175 kg/mm², respectively. The more rigid PI2610 exerts a larger constrain force on the metallization and retards the diffusion of the metal atoms. Hence, the lifetime for P26 passivated samples is longer than that of P25 passivated ones.

As discussed previously, in the multilayer interconnects, failure is not catastrophic open failure, as the

TABLE II Failure time radio for Cu multilayer interconnect under various stressing conditions

Stressing conditions	t_{P25M}/t_M	t_{P26M}/t_M	$t_{P26M}/t_M/t_{P25M}/t_M$
170 °C, $J = 3.42$ MA/cm²	2.8	5.5	3.4
190 °C, $J = 3.42$ MA/cm²	2.9	5.7	2.5
210 °C, $J = 3.42$ MA/cm²	1.9	8.3	4.5
230 °C, $J = 3.42$ MA/cm²	2.1	6.5	2.9
230 °C, $J = 2.28$ MA/cm²	4.2	12.6	2.9
230 °C, $J = 2.85$ MA/cm²	3.0	16.2	4.5
230 °C, $J = 4.0$ MA/cm²	3.0	11.8	3.5

* t_{P25M} and t_M are the failure time of Cu multilayer passivated with polyimide PI 2540(P25/TiWN/Cu/TiWN/P25/Si) and the unpassivated Cu multilayer (TiWN/Cu/TiWN/P25/Si), respectively.

TABLE III Failure time ratio for Cu multilayer interconnect to the Cu monolayer interconnect under various stressing conditions

Stressing conditions	t_{M25}/t_{S25}	t_{PM25}/t_{PS25}	t_{PM26}/t_{PS26}
170 °C, $J = 3.42$ MA/cm²	3.0	1.7	1.2
190 °C, $J = 3.42$ MA/cm²	2.4	5.3	1.4
210 °C, $J = 3.42$ MA/cm²	2.0	3.1	1.6
230 °C, $J = 3.42$ MA/cm²	1.6	3.1	1.1
230 °C, $J = 2.28$ MA/cm²	1.3	—	1.2
230 °C, $J = 2.85$ MA/cm²	2.1	1.7	2.2
230 °C, $J = 4.0$ MA/cm²	3.3	9.3	1.2

* $t_{S25}, t_{M25}, t_{PM25},$ and t_{PS25} are the failure time of Cu monolayer on polyimide PI2540 (Cu/P25//Si), Cu multilayer on PI2540 (TiWN/Cu/TiWN/P25/Si), passivated (with PI2540) Cu multilayer on PI2540 (P25/TiWN/Cu/TiWN/P25/Si) and passivated Cu monolayer on PI2540 (P25/Cu/P25/SI), respectively.

barrier layer still maintains electrical continuity at local gaps in the Cu layer. Hence, one would expect that the multilayer structure has longer lifetime than the monolayer interconnect does. Table III gives a comparison between the lifetime of Cu multilayer and Cu monolayer interconnects. The time to failure of Cu multilayer is longer than that of Cu monolayer, as expected.

Conclusions

The effect of polyimide passivation on the EM of Cu multilayer (TiWN/Cu/TiWN) interconnect is investigated. An oscillation in resistance is observed during the isothermal resistance measurements. Formation and closing of gaps in the Cu-layer is one of the possibilities that causes the resistance oscillation. The activation energy for EM of the passivated Cu multilayer is larger than that of the unpassivated one. The passivated Cu multilayer interconnect has better EMD resistance and a lifetime 2–6 times longer than the unpassivated one. The interlayer TiWN not only serves as adhesion and diffusion barrier layer, but also maintain electrical continuity during the formation of Cu gaps. Hence, the time to failure of Cu multilayer is larger than that of Cu mono-layer. The EM resistance of copper metallization is enhanced by employing passivation and a multilayer structure.

References

1. J. W. MCPHERSON, H. A. LE and C. D. GRASS, *Microelectron. Reliab.* **37** (1997) 1469.
2. J. TAO, N. W. CHEUNG, C. HU, H. KANG and S. S. WONG, *IEEE Electron Device Lett.* **13** (1992) 433.
3. J. TAO, N. W. CHEUNG and C. HU, *ibid.* **14** (1993) 249.
4. H. W. WANG, B. S. CHIOU and J. S. JIANG, *J. Mater. Sci.: Mater. Electronics*, **10** (1995) 267.
5. H. W. WANG and B. S. CHIOU, *ibid.* **11** (2000) 17.
6. J. S. JIANG and B. S. CHIOU, *Int. J. Microcircuits Electron. Packag.* **22** (1999) 395.
7. J. S. JIANG and B. S. CHIOU, *ibid.* **23** (2000) 501.
8. C. K. HU, K. Y. LEE, K. L. LEE, C. CABRAL, JR., E. G. COLGAN and C. STANIS, *J. Electrochem. Soc.* **143** (1996) 1001.
9. A. SCORGONI, I. DEMUNARI, R. BALBONI, F. TAMARRI, A. GARULLI and F. FANTINI, *Microelectron. Reliab.* **36** (1996) 1691.
10. J. TAO, N. W. CHEUNG and C. HU, *IEEE. Trans. Electron Devices* **43** (1996) 1819.
11. T. NITTA, T. OHMI, T. HSOHI, S. SAKAI, K. SAKAIBARA, S. IMAI and T. SHIBATA, *J. Electrochem. Soc.* **140** (1993) 1131.
12. C. K. HU and J. M. E. HARPER, *Mater. Chem. Phys.* **52** (1998) 5.
13. R. ROSENBERG and L. BERENHAUM, *Appl. Phys. Lett.* **12** (1968) 201.
14. M. SHATZKES and J. R. LLOYD, *J. Appl. Phys.* **59** (1986) 3890.
15. R. E. HUMMEL, R. T. DEHOFF and H. J. GEIER, *J. Phys. and Chem. Solids* **37** (1976) 73.
16. R. A. SIGSBEE, *J. Appl. Phys.* **44** (1973) 2533.
17. C. K. HU and B. LUTHER, *Mater. Chem. Phys.* **41** (1995) 1.
18. T. FUKADA, T. MORI, Y. TOYODA, M. HASEGAWA, K. NAMBA, and K. OGATA, *Appl. Surf. Sci.* **91** (1995) 227.