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Passivation film damage during focused ion beam IC modification

Jiaming Ge
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modification**

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San Jose State University, 1993

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PASSIVATION FILM DAMAGE
DURING FOCUSED ION BEAM IC MODIFICATION

A Thesis
Presented to
The Faculty of the Department of Materials Engineering
San Jose State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

By
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May, 1993

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ABSTRACT

PASSIVATION FILM DAMAGE DURING FOCUSED ION BEAM IC MODIFICATION

by Jiaming Ge

This thesis addresses the issue of passivation film damage during focused ion beam IC modification. Patterned wafers with both PSG and silicon nitride as the passivation film were examined using focused ion beam technology to characterize one common damage mechanism associated with the passivation film and to study the factors which determine the failure incidence. The influence of specimen temperature, ion flux, traverse velocity, and ion energy on the occurrence of passivation film failure events was investigated. It is proposed that liquid gallium condensation inside pre-existing pores results in short-circuiting of surface charge to underlying, grounded aluminum metallization lines. The surface diffusion of Ga^+ ions to and along the defects controls the kinetics of the observed failure events. The activation energy of the failure process was determined to be 0.26 eV. The results suggest that focused ion beam causes passivation film damage only if defects pre-exist in the film. Therefore, the focused ion beam method can be a powerful defect-finding tool for checking the quality of both the passivation film and dielectrics in general.

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CHAPTER 1

INTRODUCTION

In the past ten years focused ion beam technology has advanced in various aspects of the semiconductor industry, including direct write implantation, lithographic resist exposure, micromachining of optical structures, circuit modification and restructuring, and repair of photolithography masks. The last two applications are of special interest since they take full advantage of the ability of the focused ion beam to image, mill, and deposit material with submicron resolution without the use of masks or resists. By ion milling it is meant that material is removed by scanning the ion beam over a selected region, thus sputtering away the unwanted feature. Alternatively, material is deposited by introducing a vapor (metal compound precursor, for example) containing the desired element and using the ion beam to locally dissociate molecules adsorbed on the surface. This process is called ion beam induced chemical vapor deposition. Commercially, this dual capability of focused ion beams has now been built into focused ion beam systems. By utilizing focused ion beam systems, integrated circuits (ICs) can be modified by drilling, cutting, or adding wires only a micrometer wide on prototype or engineering devices. These versatile tools are based on the liquid metal ion source, one of the brightest sources of charged particles yet invented. Among the various ion sources available, the liquid gallium ion source is the

most commonly used today in integrated circuit modification and repair systems.

It has been pointed out previously that the focused ion beam can be used to drill and cut through a passivation layer of IC devices to correct some errors in design, or to modify from one IC design to another. During this type of microsurgery, it has been observed that the passivation film over aluminum interconnects may be damaged, i.e., the integrity of the passivation film is lost at those sites. This phenomenon is called passivation film damage or passivation film failure. For example, the passivation film at certain areas, such as vias and edges of aluminum interconnects, could break, or tiny holes could form on the passivation layer just above the aluminum metallization lines. Figure 1 illustrates the passivation damage occurring at a via (Fig. 1a) and at an Al metallization step (Fig. 1b). The passivation failure exposes underlying Al metal and semiconductor layers to the environment. This is undesirable.

Failure of the passivation film can lead to potential problems in integrated circuits. The damage to the passivation film can not only degrade the electrical properties and multilevel wiring performance of the semiconductor devices, but also cause aluminum metallization failure over time. Damage sites are weak points which will allow moisture and sodium ions to diffuse into the devices. Corrosion and oxidation may result during the operation of the devices. Thus, the

Figure 1 (a). Scanning ion micrograph of passivation damage around a via (overview and close-up view).

Figure 1 (b). Scanning ion micrograph of passivation damage on an Al metallization step (damage is indicated by arrows).

long-time reliability of the semiconductor devices could be adversely affected. Another problem associated with the damage of the passivation layer is that in the event of charge leakage to the underlying metallization, for example, passivation film damage can cause immediate failure of the device. As far as IC modification is concerned, the damage could lower the possibility of success for IC microsurgery because the bridging of two Al interconnects must be accomplished over the passivation film.

The use of focused ion beam systems for IC modification in the semiconductor industry dates back to around 1987, and none has been reported concerning passivation film damage as a result of energetic Ga^+ ion bombardment during IC modification. The work presented here attempts to address the issue of passivation film damage. This investigation required the utilization of focused ion beam technology and the development of a specimen stage with controllable temperatures. The temperature of the specimen was controlled by employing a thermoelectric module to act as a heating or cooling stage in the focused ion beam system.

In this investigation, a patterned wafer with phosphosilicate glass (PSG) as the passivation layer was studied. Several possible damage mechanisms were proposed to explore the reasons which may be responsible for passivation film damage during focused ion beam microsurgery of passivated ICs. Some are temperature-

dependent; some are not. Additionally, some of the mechanisms are quite sensitive to the rate of charge build-up per unit time; some are not. By controlling one of these parameters, temperature, for example, and holding all others constant, the change in the frequency of passivation film failure will provide a clue as to the governing, rate-controlling mechanism. In these studies, specimen temperature is controlled, and the beam current is varied for a constant charge dosage to see how the failure/damage probability changes. Through the investigation of temperature and charge effects on the passivation film failure, the damage mechanism that is operative may be identified.

CHAPTER 2

PASSIVATION FILMS

Before damage or failure of the passivation layer in IC devices during focused ion beam processing can be considered, it is necessary to characterize the properties and defect state of the deposited dielectric films. This will be done in the following subsections.

2.1 Dielectric Films

Dielectric films have many applications in the semiconductor industry. They are used for insulation between conducting layers, for diffusion and ion implantation masks, as diffusion sources (doped oxides), for capping doped films to prevent the loss of dopants, for gettering impurities, and for passivation to protect devices from impurities, moisture, and scratches. The most widely used materials for dielectric films in VLSI technology are silicon dioxide including phosphorus-doped silicon dioxide (usually called P-glass, phosphosilicate glass, or PSG); borophosphosilicate glass (BPSG) formed when boron is added in addition to phosphorus; plasma-deposited silicon dioxide; stoichiometric silicon nitride; and plasma-deposited silicon nitride.

Of the many methods available for depositing thin dielectric films, various chemical vapor deposition (CVD) techniques are most

often used for semiconductor processing. The common deposition methods are atmospheric-pressure chemical vapor deposition (APCVD), low-pressure chemical vapor deposition (LPCVD), and plasma-enhanced chemical vapor deposition (PECVD or plasma deposition). These chemical depositions occur under a variety of conditions. Deposition temperatures vary from 100 to 1000°C, and pressures range from atmospheric down to about 7 Pa (0.05 Torr). The energy for the reaction can be supplied thermally, by photons (photochemically), or by a glow discharge. Table 1 lists some typical reactants that may be used to deposit films on device wafers. The choice of a particular reaction is often determined by the deposition temperature, which must be compatible with the device materials, the film properties, and certain engineering aspects of the deposition, such as wafer throughput, safety, and reactor maintenance.

The most common reactants for depositing silicon dioxide for VLSI circuits are oxidizing silane, SiH_4 , with oxygen at 400 to 450°C; decomposing tetraethoxysilane, $\text{Si}(\text{OC}_2\text{H}_5)_4$, at 650 to 750°C; and reacting dichlorosilane, SiCl_2H_2 , with nitrous oxide, N_2O , at 850 to 900°C⁽¹⁾. Doped oxides are prepared by adding a dopant to the deposition reaction. Silicon nitride is prepared by reacting silane and ammonia at atmospheric pressure at 700 to 900°C, or by reacting dichlorosilane and ammonia at reduced pressure at 700°C^(1,2). Plasma-deposited silicon nitride is deposited by reacting silane with ammonia or nitrogen in a glow discharge between 200 and 350°C⁽¹⁾.

Table 1. Typical Reactants for Depositing Dielectrics⁽¹⁾

Product	Reactants	Deposition Temperature, °C
Silicon dioxide	$\text{SiH}_4 + \text{CO}_2 + \text{H}_2$	850-950
	$\text{SiCl}_2\text{H}_2 + \text{N}_2\text{O}$	850-900
	$\text{SiH}_4 + \text{N}_2\text{O}$	750-850
	$\text{SiH}_4 + \text{NO}$	650-750
	$\text{Si}(\text{OC}_2\text{H}_5)_4$	650-750
	$\text{SiH}_4 + \text{O}_2$	400-450
Silicon nitride	$\text{SiH}_4 + \text{NH}_3$	700-900
	$\text{SiCl}_2\text{H}_2 + \text{NH}_3$	650-750
Plasma silicon nitride	$\text{SiH}_4 + \text{NH}_3$	200-350
	$\text{SiH}_4 + \text{N}_2$	200-350
Plasma silicon dioxide	$\text{SiH}_4 + \text{N}_2\text{O}$	200-350

This reaction is useful for depositing passivation coatings over finished devices in cases where higher temperatures cause unwanted reactions between the silicon and the metal conductors. Similarly, plasma-deposited silicon dioxide is formed from silane and nitrous oxide in a glow discharge.

Plasma-assisted depositions provide films at low substrate temperatures. They do so by reacting the gases in a glow discharge. The discharge ionizes the gases, creating active species that react at the wafer surface. This technique is referred to as plasma deposition^(3,4). Many inorganic and organic materials have been deposited by plasma deposition, but only two are useful in VLSI technology: plasma-deposited silicon nitride and plasma-deposited silicon dioxide. Plasma-deposited silicon nitride is used as the encapsulating material for the final passivation of devices. The plasma-deposited nitride provides excellent scratch protection, serves as a moisture barrier, and prevents sodium diffusion. Because of the low deposition temperature, i.e., 300 to 350°C, the nitride can be deposited over the final device metallization. Plasma-deposited silicon nitride and silicon dioxide are both used as insulators between metallization levels. They are particularly useful when the bottom metal level is aluminum or gold.

2.1.1 Silicon Dioxide

Silicon dioxide films can be deposited with or without dopants. Undoped silicon dioxide is used as an insulating layer between multilevel metallizations, as an ion-implantation or diffusion mask, as a capping layer over doped regions to prevent out-diffusion during heat cycles and to increase the thickness of thermally grown oxides. Phosphorus-doped silicon dioxide (typical dopant concentrations are 4 to 6 wt pct phosphorus) is used as an insulator between metal layers, as a final passivation over devices, and as an impurity gettering source.

The processing sequence for silicon dioxide depends on its specific use in the device. Oxides used as insulators between conducting layers are deposited, densified by annealing, and etched to open windows. A solution containing fluoride or a CHF_3 plasma etches the oxide. Phosphorus-doped oxides, used in the flowed glass process, are heated to a temperature between 950 and 1100°C so that the oxide softens and flows, providing a smooth topography. This improves the step coverage for the next metallization layer. Phosphorus-doped oxides used for passivation are deposited at temperatures lower than 400°C, and areas for bonding are opened by etching.

Table 2 summarizes properties of silicon dioxide deposited by

Table 2. Properties of Silicon Dioxide(1)

Deposition	Plasma	SiH ₄ + O ₂	TEOS*	SiCl ₂ H ₂ + N ₂ O	Thermal
Temperature (°C)	200	450	700	900	1000
Composition	SiO _{1.9} (H)	SiO ₂ (H)	SiO ₂	SiO ₂ (Cl)	SiO ₂
Thermal stability	loses H	densifies	stable	loses Cl	stable
Density (g/cm ³)	2.3	2.1	2.2	2.2	2.2
Refractive index	1.47	1.44	1.46	1.46	1.46
Stress (10 ² MPa)	3C - 3T	3T	1C	3C	3C
Dielectric strength (10 ⁶ V/cm)	3 - 6	8	10	10	11
Dielectric constant	4.9	4.3	4.0	--	3.9

* TEOS is the abbreviation for the compound tetraethoxysilane, Si(OC₂H₅)₄.

different techniques, including plasma-assisted deposition. In general, oxides deposited at higher temperatures resemble thermally grown silicon dioxide. However, high-temperature oxides cannot be deposited over aluminum and therefore cannot be used for the final device passivation or for insulation between aluminum levels. Consequently, the low-temperature, phosphorus-doped oxides are used in spite of their poor step coverage and somewhat inferior film properties.

Silicon dioxide deposited at low temperatures (400-500°C) contains hydrogen. This hydrogen is bonded within the silicon-oxygen network as silanol (SiOH), hydride (SiH), or water (H_2O) (5). The bonded hydrogen can be detected by infrared spectroscopy. Silicon dioxide films deposited at 700°C by the decomposition of tetraethoxysilane, $\text{Si}(\text{OC}_2\text{H}_5)_4$ (abbreviated TEOS), or at 900°C by the dichlorosilane-nitrous oxide reaction, do not contain hydrogen that is detectable by infrared absorption. The films formed from dichlorosilane, however, contain chlorine. Deposited silicon dioxide has an amorphous structure consisting of SiO_4 tetrahedra(6).

Stress in silicon dioxide depends on deposition temperature, deposition rate, annealing treatments, dopant concentration, water content, and film porosity(7). Undoped silicon dioxide deposited at a temperature between 400 and 500°C usually has a tensile stress of 100 to 400 MPa. Undoped oxides deposited at a temperature

between 650 and 750°C have a low compressive stress, 0 to 100 MPa. Oxides deposited at 900°C have a slightly higher compressive stress, 200 to 300 MPa. The stress state in oxides is strongly influenced by impurities. The stress is usually more compressive when phosphorus is added, but is more tensile if the film contains water⁽¹⁾.

2.1.2 Silicon Nitride

Stoichiometric silicon nitride (Si_3N_4) is used for passivating silicon devices because it serves as an extremely good barrier to the diffusion of water and sodium. If present, these impurities can cause device metallization to corrode or devices to become unstable. Silicon nitride, chemically deposited at temperatures between 700 and 900°C, is an amorphous dielectric containing up to 8 at pct hydrogen. The hydrogen is bonded to the nitrogen and the silicon. The amount of hydrogen depends on the deposition temperature and the ratio of reactants. More hydrogen is incorporated at low deposition temperatures or at high ammonia to dichlorosilane ratios⁽¹⁾.

Silicon nitride has a high tensile stress, about 1×10^3 MPa. Films thicker than 200 nm sometimes crack because of the high stress. The resistivity of silicon nitride at room temperature is about 10^{16} ohm-cm. The electrical resistivity depends on the deposition temperature,

film stoichiometry, amount of hydrogen in the film, and the presence of oxygen impurities.

Stress is one of the most important properties of plasma silicon nitride, since high stress can cause cracking of the nitride film. Crack-free films with low tensile stress, less than 200 MPa, can be prepared, but the deposition conditions must be carefully established and controlled. Stress depends not on the film composition but on the local bonding around individual atoms⁽⁶⁾. Deposition variables such as temperature, rate, and ionic bombardment have large effects on the film stress⁽¹⁾.

Table 3 summarizes the general properties of LPCVD silicon nitride and plasma-deposited nitride. The properties of plasma nitride vary over large ranges because the film composition is variable.

2.2 Defects in Passivation films

In section 2.1, common dielectric materials for IC applications, primarily for passivation films or for dual dielectrics of MOS devices, were reviewed. It has been reported that defects of various types in glass passivation layers are frequently introduced during CVD of the films, or during processing steps associated with glassing, such as

Table 3. Properties of Silicon Nitride⁽¹⁾

Deposition	LPCVD	Plasma
Temperature (°C)	700-800	250-350
Composition	Si ₃ N ₄ (H)	SiN _x H _y *
Si/N ratio	0.75	0.8 - 1.2
Atom % H	4 - 8	20 - 25
Refractive index	2.01	1.8 - 2.5
Density (g/cm ³)	2.9 - 3.1	2.4 - 2.8
Dielectric constant	6 - 7	6 - 9
Resistivity (ohm-cm)	10 ¹⁶	10 ⁶ - 10 ¹⁵
Dielectric strength (10 ⁶ V/cm)	10	5
Stress (10 ² MPa)	10 T	2C - 5T

* The x and y can be calculated according to Si/N ratio and atom % H.

surface preparation and photolithography⁽⁶⁾. Dust or reaction products in the gas or vapor streams or on the substrate surface during chemical vapor deposition interfere with film nucleation and proper growth, resulting in voids, thin spots, partial or complete pinholes, or hillocks. Pinholes in the films can also be generated if the photoresist does not protect the film completely. The presence of localized defects, such as pinholes, cracks, and other discontinuities in the passivation layers, has been confirmed by time-dependent corrosion of aluminum metallization lines, observed during humidity testing⁽⁸⁾, and by breakdown characteristics of MOS capacitors⁽⁹⁾. During both time- and field-dependent dielectric breakdown testing, localized defects in oxide films serve as the weak spots at which dielectric failure occurs.

Stresses are developed in silicon nitride and silicon dioxide as a result of differential thermal expansion between the deposited films and the substrate. Based on thermomechanical theory and the thermal coefficient of expansion mismatch between aluminum-silicon metallization, silicon nitride, and silicon dioxide, mechanical modeling indicates that compressive stress results in the passivation dielectric layer and tensile stress within the Al metallization⁽¹⁰⁾. The principal stress pattern in the cross sectional plane of an encapsulated 2 μm wide Al-Si line at 25°C is shown in Figure 2. Typical material properties used in the stress modeling are listed in Table 4.

Figure 2. (a) Principal stress pattern in the cross sectional plane of an encapsulated 2 μm wide Al-Si line at 25°C. Tensile stresses are represented by arrow heads and compressive stresses by perpendicular tail bars. Only the right half of the symmetric geometry is shown. (b) Layer identification. (After Jones, Ref. 10.)

**Table 4. Typical Material Properties* of Thin Film Layers
in Integrated Circuits⁽¹¹⁾**

	Modulus of Elasticity (GPa)	Thermal Expansion Coef. (10^{-6} /°C)
Silicon Substrate	131.0	2.3
Al-Si Metallization	70.3	23.5
Silicon Nitride	89.6	2.2
Silicon Dioxide	79.9	0.5

*All material properties shown are at 25°C.

According to Figure 2, the stresses in the aluminum metallization are all tensile and relatively uniform with the tangential stress nearly the same as the maximum principal stress in the cross sectional plane. At the corners of the metallization line, high compressive stresses occur in the passivation, but the principal stresses do not all have the same sign. Tensile components could easily give rise to passivation cracking. Cracks are very common and important localized defects in passivation films and are caused by stress⁽⁷⁾.

An additional complication not considered in Figure 2 is that passivation films can be deposited with an initial, residual stress, either tensile or compressive, depending on the material and process history. These stresses would linearly superpose with the stress field indicated in Figure 2. And thus, the magnitude and sign of the total stress field is greatly affected by the deposition conditions. Stresses in the passivation film may be predominantly tensile.

An attempt to explain damage of passivation films induced by focused Ga^+ ion exposure must assume the pre-existence of defects.

CHAPTER 3

POSSIBLE DAMAGE MECHANISMS

The composition of passivation films, stress condition, and defect state, together with the interaction of Ga^+ ions during focused ion beam operations, may cause passivation film failure. In this chapter possible damage mechanisms are proposed and discussed.

3.1 Heating Effect of Focused Ion Beam

Heating due to the focused ion beam has been reported⁽¹⁾. The model of heat flow is shown in Figure 3. An equation used to calculate the temperature rise above the background at some distance ρ from where a submicron ion beam irradiates is expressed as follows⁽¹²⁾:

$$\Delta T = T(\rho) - T(\infty) = (Vi/2k)(r^2/\rho) \quad \text{Eq. (1)}$$

where V : acceleration voltage of focused ion beam

i : current density of focused ion beam

k : thermal conductivity of the passivation film

r : radius of focused ion beam

ρ : radius from the center of the beam on the surface

(spherical coordinates)

When the radius $\rho = r$, Eq. (1) predicts the highest temperature.

Figure 3. Geometry for considering heat flow at point of ion beam incidence. (After Melngailis, Ref. 12.)

Table 5 lists local temperature increases, as predicted by Eq. (1), for silicon dioxide film as a calculation example. The focused ion beam is assumed to be at a constant acceleration voltage of 30 kV and the ion beam current densities (corresponding to different aperture sizes) are as indicated in Table 5. The aperture diameter, d , can be considered to be the diameter of the focused ion beam. The assumed current densities for this non-rastered ion beam yield temperature rises ranging from 10 to 40°C. The thermal conductivity of silicon dioxide used in this calculation is $k = 1.5 \text{ W/m}^\circ\text{K}$.

Local heating may lead to the increase of stress in the glass or a change of stress state between the passivation film and underlying aluminum metallization lines due to the large difference of thermal expansion coefficient, specific heat, and heat conductivity between Al metallization and the passivation layer. Tensile components of stress may propagate existing flaws in the passivation film; thus, passivation film cracking could result.

3.2 Implantation Effect of Ga^+ Ion Beam

When Ga^+ ions impinge on the surface of passivation films, some Ga^+ ions will implant. As a result, the implanted glass film will swell, and the specific volume of the glass will increase. Therefore, the compressive stress in the passivation films will increase and the

**Table 5. Temperature Increase in Silicon Dioxide Film
Due to Ion Beam Irradiation**

Ion Beam Diameter d, (μm)	Ion beam current density i, (A/cm ²)	Temperature increase ΔT, (°C) at ρ/r =1
2.00	0.197	39.4
0.50	0.816	40.8
0.20	1.274	25.8
0.10	1.290	12.74
0.05	2.296	11.48

Note: The ion beam current density is determined by

$$i = I/\pi d^2/4$$

where I is the ion beam current, which depends on the aperture size, d.

glass may lift off the aluminum metal. Of course, this will be dependent upon the amount of Ga^+ ions implanted and the mean depth of implantation for a given process condition. Local heating may increase dramatically because of the lift-off, and the underlying substrate may no longer serve as an efficient thermal sink. Severe damage to the passivation film, cracking and lift-off, may result.

3.3 Surface Charging Effect of Ga^+ Ions

Semiconductor devices can be considered as metal-insulator composite structures. As the Ga^+ ions bombard passivation films, positive charges build up on the passivation films. Thus, the passivation film is stressed electrostatically. At some critical electric field, passivation film breakdown occurs and discharge to the grounded metallization lines may result. Because the Ga^+ ion beam is rastered back and forth across the specimen, the electrostatically-induced stress is therefore cyclic. The mechanical integrity of the film may thereby be reduced.

3.4 Composition Effect of Passivation Films

Passivation films always contain some dissolved hydrogen ($\text{Si}_3\text{N}_4 \sim 4\text{-}8$ at pct H, and $\text{SiN} \sim 20\text{-}25$ at pct H) and other dissolved gases. Hydrogen in silicon dioxide exists as SiOH , or SiH , typically

1-4 wt pct SiOH and less than 0.5 wt pct SiH⁽⁶⁾. These trapped gases are either byproducts of the chemical vapor deposition process or the sputter gas in the case of physical sputter deposition process. The trapped gases may evolve during ion bombardment, and as a result, the specific volume of the passivation film may be reduced locally (i.e., the specific volume of passivation film with low content of hydrogen is smaller than that of passivation film with high percentage of hydrogen). Therefore, the stress state in the passivation films where the beam is hitting will become more tensile (less compressive) in character. Passivation microfractures could result.

3.5 Liquid Gallium Formation

When Ga⁺ ions are incident on the passivation film, Ga⁺ ions will be collected on that surface, which is a natural occurrence of deposition. The surface density of a solid is about 2×10^{15} atoms/cm², which is the number of atoms required to form a monolayer of material. Assuming that all Ga⁺ ions fluxed to the surface of the rastered area are collected on that surface, if the number density of these Ga⁺ ions is significantly larger than 2×10^{15} atoms/cm², Ga⁺ ions will cluster as they are neutralized; as a result, liquid gallium may form. If the pre-existing cracks or pinholes extend to underlying Al metallization lines, capillary-pull of liquid gallium into these defects

could lead to continuous electrical contact to the underlying Al metallization lines.

It does not take a great number of neutralized gallium atoms to "cluster" to form liquid gallium within a tight pore. Ga atom transport to and down defects may lead to formation of liquid gallium within the defect when the number density of Ga^+ ions irradiating the surface is not large enough to provide heterogeneous nucleation at the free surface. Figure 4 schematically illustrates how pre-existing flaws or pinholes may serve as local sites for gallium liquification. The number of Ga^+ ions necessary to meet the critical radius for heterogeneous nucleation of liquid gallium is much less than the number needed if the pores were not present⁽¹³⁾. In this case, liquid gallium may only form in the vertical pinholes or flaws, not on the free surface. The liquid in the capillary pore may supercool considerably below T_m , the melting temperature, before transformation to the solid state would occur. The formation of liquid gallium in defects may ultimately lead to liquid gallium contact with the underlying aluminum metal.

One outcome of liquid gallium contact with Al metallization lines in a tensile state is liquid gallium embrittlement. The fracture of underlying aluminum metallization lines may result in passivation film damage. However, a more probable consequence is the discharge

Figure 4. Cross section of a tight pore showing the formation of liquid gallium.

of the positive surface charge to the grounded metallization line and the consequent incipient melting of the metal line.

3.6 Surface Diffusion of Ga^+ Ions

Surface diffusion of Ga^+ ions to and along cracks or pinholes could become a possible rate limiting mechanism responsible for passivation failure when the number of Ga^+ ions collected on the exposed passivation film is less than 10^{15} ions/cm², too few for monolayer coverage. The existing defects in the passivation layer may serve as paths for Ga^+ ion transport to the underlying aluminum wire. Electrical shorting may develop between the highly positive-charged passivation layer and the grounded Al metallization lines. When the electrical shorting occurs, the power surge to the Al film could cause passivation film damage, or local melting of the metallization line.

When incident Ga^+ ions are stopped by the passivation layer, they are neutralized. The neutralized Ga^+ ions at the surface of the glass layer are only weakly bound, so that surface diffusion of gallium is much faster than bulk diffusion. Furthermore, the surface diffusion is also a kinetic process, controlled by the Arrhenius relation. Therefore, the activation energy will be a critical factor in speculating whether the Ga^+ ion induced passivation film failure is an operative mechanism or not. Since the number of ions on the surface

is small, the coverage of Ga^+ ions would affect the activation energy. Honda and Okano⁽¹⁴⁾ have reported that the activation energy of surface diffusion of Ga atoms on a Ge surface decreases as the coverage increases with a maximum reduction of the activation energy reached at about 0.2 eV. Figure 5 shows the activation energy as a function of monolayer (ML) coverage of gallium atoms.

Figure 5. Activation energy of surface diffusion of Ga on Ge. (After Honde and Okano, Ref. 14.)

CHAPTER 4

EXPERIMENTAL

As mentioned before, passivation film failure or passivation film damage can occur during focused ion beam modification (or microsurgery). Regions where a passivation film is deposited over steps of aluminum metallization lines or over vias are particularly susceptible to damage during focused ion beam bombardment. In some cases, the underlying Al metal lines become exposed to the environment. To measure the susceptibility of a passivation film to focused ion beam damage, the failure incidence, defined as the number of events per centimeter of the aluminum metallization line, is used. The main focus of this research is to identify one or two failure modes associated with the damage of passivation film and to study the factors which determine the failure incidence.

4.1 Apparatus

To examine the failure incidence of the passivation layer at various temperatures during gallium ion bombardment, a conventional Focused Ion Beam (FIB) system modified with a solid state heat pumping specimen holder was employed. Figure 6 shows a schematic drawing of the focused ion beam optics column of the FIB system Model SMI 8300, manufactured by Seiko Instruments, Inc., Oyama plant, Japan. The two-lens ion column delivers Ga^+ ions of

Figure 6. Schematic drawing of focused ion beam optics system used in the investigation. (After Nikawa et al, Ref. 15.)

energies between 5 and 50 keV at beam diameters as small as 0.05 μm .

Constant ion flux is established in the system by selecting the proper combination of magnification and objective aperture. The focused ion beam system has an imaging capability known as Scanning Ion Microscopy (SIM). Where the Ga^+ ion beam is incident, secondary electrons are emitted. The secondary electrons are collected by a detector composed of a photomultiplier tube and a scintillator, and the signal from the detector is used to modulate a cathode ray tube. The shallow penetration of Ga^+ ions results in higher resolution of specimen topography when compared with conventional scanning electron microscopy. The yield of secondary electrons caused by impingement of Ga^+ ions depends on the work function of the target material, and thus FIB is capable of distinguishing, for example, aluminum metal from dielectrics. The SIM function is very useful for in-situ observation.

Temperature control is critical during this study. In order to achieve the desired specimen temperature within the focused ion beam system, a thermoelectric (TE) module with a size of 35x35x5 mm (manufactured by Tellurex Corporation, Traverse City, MI) was used, as shown in Figure 7. The TE module is a small heat pump based on the Peltier effect. In function, it is similar to a conventional refrigeration unit. A module is comprised of an array of

Figure 7. Schematic view of a thermoelectric module with the sample placed on the device surface. (Ref. 16.)

semiconductor couples connected electrically in series and thermally in parallel, sandwiched between ceramic substrates. When a thermoelectric module is connected to a DC power supplier (typically, 5 volts and 3 amps for this study), heat is absorbed at one surface of the device (the surface being cooled) while heat is rejected at the other surface (the surface being heated). The TE module was mounted on the sample stage of the focused ion beam system. The specimen was affixed to the TE module using silver glue and was electrically grounded to the FIB sample stage. By varying the module input power, steady-state temperatures ranging from 15°C to 45°C were obtained. Through a vacuum power feedthrough, an in-situ thermistor indicated the temperature of the specimen.

4.2 Wafer Selection

IC modifications have been performed by the author on many patterned wafers from various commercial vendors. The passivation film damage does not occur to the same degree on every wafer during integrated circuit microsurgery. To conduct the experiment effectively, care was taken to select wafers which have demonstrated susceptibility to damage of a given type and that show a reproducible failure incidence for a given set of FIB conditions. A subset of suitable wafers were selected for the study. These wafers demonstrated consistency in generating the desired Ga^+ ion induced defects (i.e., passivation film failure) and exhibited a particular and

common type of passivation film failure, at the edge of aluminum metallization lines, over the entire patterned wafer. The patterned wafer used in this study was examined in the as-received condition. The specific failure modes will be fully characterized in this report.

The wafer of study is 0.15 meter in diameter with dies (12 mm by 12 mm each) fabricated on the (100) Si substrate using CMOS technology. The plan view of the multilayered structure is shown in Figure 8. A schematic cross-sectional view of the patterned structure shown in Figure 8 is illustrated in Figure 9. This structure is composed of passivation film (phosphosilicate glass, or PSG) of thickness 1 μm , top level aluminum metallization (commonly called metal 2, or M2) with thickness of 0.8 μm , and bottom level aluminum metallization (metal 1, or M1) with thickness of 0.7 μm . A dielectric film of plasma enhanced CVD SiO_2 was used between M1 and M2, and BPSG was used between M1 and the (100) Si substrate. The composition of the aluminum alloy film was Al - 0.5%Cu - 1.5%Si (by weight). To facilitate the experiments, the wafer was cut into several pieces with the dimension of 6 mm by 12 mm per piece. Each specimen for failure characterization represents the same location on the die.

Experimental study of failure incidence on one other wafer, similarly processed and from the same vendor, with PSG as the passivation layer was conducted, and the results from the two

Figure 8. SEM micrograph of the patterned structure with double-layer Al metallization for the study of passivation film damage. The top Al line (horizontal) is usually called metal 2 (M2), and the bottom (vertical) metal 1 (M1).

Figure 9. A schematic cross-sectional view of the patterned wafer shown in Figure 8.

batches are compared herein. One other wafer from the same vendor with similar IC design but with silicon nitride as the passivation layer was also studied.

4.3 Methodology

Unless otherwise indicated, all experiments were conducted at Ga^+ ion energy of 30 keV, which, in the absence of pinholes, cracks, or other defects, should be able to penetrate through only a few percent of the PSG thickness overlaying the top layer of aluminum.

During the IC modification, the focused ion beam is used to scan an area. The area scanned is proportional to the square of the magnification setting. During the rastering process, there is some flux of ions which, if the beam scan rate and accelerating voltage are held constant, will vary with area scanned; that is, with magnification.

In order to see the influence of ion beam current on the occurrence of failure events, the rastered beam current density is defined as follow:

$$J = I/A \quad \text{Eq. (2)}$$

where I: the focused ion beam current in amps

A: the area of the rastered region in cm^2

Therefore, the ions fluxed to the rastered area can be calculated from the following equation, assuming every gallium ion is singly charged (17).

$$\text{Ion flux} = q/tAe = I/Ae \quad \text{Eq (3)}$$

Where:

t: time in sec

e: charge of an electron, equal to 1.6×10^{-19} coulombs

q: charges incident on the scanned area within time, t, in coulombs

Table 6 lists the rastered beam current density values used in this research and the corresponding ion fluxes.

When the raster-area of the focused ion beam is incident on the M1 aluminum metallization lines, the velocity of the sample stage can be varied to control the total exposure. The velocity of specimen motion past the ion beam exposure window is termed the traverse velocity, v, in this report. When the sample stage is translated, the exposure area is centered along the symmetric axis of the metal line. Since the width of a passivated metal 1 line is about 10 μm , and since the typical exposure window is greater than 10 μm on an edge, both edges of the line are rastered within the exposure window. Most of the experiments were conducted at a velocity of 4.85 $\mu\text{m}/\text{sec}$, and

Table 6. Current Density vs. Ion Flux

Current density (10 ⁻² mA/cm ²)	Ion flux (10 ¹³ ions/cm ² sec)
1.04	6.50
1.11	6.90
2.50	16.0
3.82	24.0
4.17	26.0
6.94	43.0
8.59	54.0
9.37	59.0
15.28	96.0

the resulting accumulated ion dose within the rastered area of the passivation film is obviously greater than 10^{13} ions/cm², according to Table 6.

4.3.1 Temperature Effect

The studies of failure incidence of the passivation film in the temperature regime of interest and at various ion fluxes were conducted by translating the rastered Ga⁺ ion beam along the metal 1 interconnection and controlling the input power of the TE module. The ion flux was set by using different apertures at a fixed magnification or by changing magnification at a fixed aperture setting. Because the passivation film failure occurring above the metal 1 interconnection is more reproducible than that above metal 2, the Ga⁺ ion beam was irradiated only along the aluminum metal 1 line for a given test. The patterned wafer provided a high linear density of metal 1 line where the metal 2 layers do not intersect.

4.3.2 Statistical Variation

To examine the statistical distribution of failure events, experiments conducted at temperatures of 25 and 30°C were repeated 5 times. Thus, one set of data consists of 5 values, and the mean and variation in failure incidence were determined.

4.3.3 Velocity Effect

To test whether the defects nucleate and grow at specific sites during Ga^+ ion impingement (i.e., if sites are already there due to the IC processes), the specimen stage was translated so as to pass the Ga^+ ion beam exposure window at velocities from 0.66 to 49.6 $\mu\text{m}/\text{sec}$, for a constant ion flux, along the steps of the M1 passivation overlay (See Figure 8). The failure incidence in this velocity test was measured in units of events per centimeter. The rationale is that if specific sites are present, then the number of failure events per unit length should come to a constant value as the velocity of the Ga^+ ion beam is reduced.

The temperature effect on the velocity dependent failure rate was also examined. And, to examine the failure trend, the failure rate versus velocity experiment was run for two wafers from the same vendor, one with PSG as passivation layer, and the other with silicon nitride as the passivation layer.

4.3.4 Accelerating Voltage Effect

To examine the influence of accelerating voltage on the subject failure mechanism, the failure rate study was also performed at different Ga^+ ion acceleration voltages. Two voltage settings, 20 kV and 30 kV, were compared.

4.3.5 Time Dependence

To evaluate the temperature dependence of the passivation film failure mechanism, the time to failure was evaluated as a function of the reciprocal of absolute temperature. For these data, the exposure window was fixed, and unexposed specimen was rapidly translated into the exposure window. The time to initiation of a failure event, as monitored in the real-time scanning ion microscopy mode, was thus determined.

4.4 Failure Mode Characterization

The morphology of the passivation film failure was examined by both scanning electron microscope and scanning ion microscope. To reveal the details of individual failure events, cross-sections of failure locations were done by using the focused ion beam system. This is accomplished by sputter-etching the specimen using submicron focused ion beam to form a cross-section of a failure location, and then tilting the specimen (usually 60°) to examine it based on the imaging capability of the scanning ion microscope.

CHAPTER 5

RESULTS AND DISCUSSION

In this section, the morphology of failure events is illustrated. Ion flux and temperature effects on the failure incidence are presented and discussed. Failure incidences between various batches of wafer are compared. Finally, the activation energy which describes the time-dependent failure event was determined.

5.1 Morphology of the Passivation Film Failure Events

Based on the observations of numerous passivation failures occurring during the FIB modification of the subject IC devices, the passivation damage events were found to consistently take place along the passivation layer step correlating with the underlying M1 aluminum metallization lines. Regardless of the temperature at which the failure event occurred, the morphology of the events can be categorized into two types as shown in Figures 10 and 11; these events are referred to as minor and major events.

Figure 12 is an SIM micrograph of typical minor and major events. For the minor event, the underlying Al metallization does not become visible in the SIM image while for the major event, the Al metal becomes exposed to the environment through discharge heating to above the melting point of the Al metallization. A high

Figure 10. SEM micrograph of a minor event on the passivation step correlating to the underlying M1 aluminum line.

Figure 11. SEM micrograph of a major event on the edge of the passivated M1 aluminum line.

Figure 12. SIM image of two types of event at a magnification of 1.0 K. Bright spot inside large hole indicates the Al metallization.

secondary electron yield results in the bright spot illustrated in Figure 12, and this can readily be observed during real-time SIM microscopy.

Passivation failure events were cross-sectioned using the focused ion beam microsurgical technique. Typical sections are presented in Fig. 13 (a) and (b) and in Fig. 14. To yield better contrast, a tungsten thin film of about 0.2 μm was deposited on the surface of the failure event prior to FIB micro-sectioning. During tungsten deposition, the failure events plug with the tungsten. Both aluminum and tungsten appear bright in the SIM micrographs in contrast to the dielectric and passivation film layer. Figure 13 suggests that tiny pores on the passivation step above the Al lines extend down to the underlying metallization. Thus, the type of damage seen in Fig 13 (a) and (b) is believed to be initiated when charges dissipate at the moment of contact of the continuous surface diffused Ga^+ ions with the underlying aluminum. Joule heating associated with the discharge melts the aluminum. The aluminum flashes, and the minor event is the result.

In Figure 14, it can be seen that part of the passivation film is lost in a major event so that the edge of the Al metallization is no longer covered by the passivation layer.

Figure 13 (a). SIM micrograph of an FIB cross-sectioned minor event occurring at the passivation step immediately above the M1 line.

Figure 13 (b). SIM micrograph of an FIB cross-sectioned minor event oblique to the M1 line.

Figure 14. SIM micrograph of an FIB cross-sectioned major event. The specimen is tilted at 60° to reveal the plane of the cross section.

5.2 Failure Incidence of the Passivation Film vs. Ion Current Density at Various Temperatures

Figure 15 shows the logarithmic plot of failure incidence of the passivation film as a function of ion current density at temperatures of 15, 20, 25, 30, 35, 40, and 45°C for a constant traverse velocity of 4.85 $\mu\text{m/sec}$. The studies were conducted on the patterned wafer with PSG as the passivation layer. The beam current density was varied from 1.04×10^{-2} to 1.53×10^{-1} mA/cm^2 , and this corresponds to a variation in ion flux from 6.5×10^{13} to 9.6×10^{14} $\text{ions/cm}^2 \text{ sec}$, respectively. Ion fluxes lower than about 6×10^{13} $\text{ions/cm}^2 \text{ sec}$ or higher than about 10^{15} $\text{ions/cm}^2 \text{ sec}$ are of no practical use to common FIB IC modification procedures.

In examining these data, it is noted that for a constant ion current density (or ion flux), as the temperature goes up, more failure events occur per length of M1 metal line. At a fixed temperature, the failure incidence increases with increase in ion flux. A notable jump in failure incidence is observed when the temperature increases from 25°C to 30°C. The melting point of gallium is 29.8°C. This indicates that the physical state of gallium may affect the failure incidence.

The temperature-dependent characteristic of failure incidence (See Fig. 15) can be rationalized in terms of gallium transport to and

Figure 15. Logarithmic plot of passivation film failure incidence as a function of ion current density at various temperatures.

down existing pores in the passivation film. Because the number density of Ga^+ ions incident on the surface of the passivation film each second (See Table 6) is close to the monolayer density of surface atoms (about 10^{15} ions/cm²), it can be assumed that there is a sufficient number density of neutralized Ga atoms in pores and cracks to cluster. The pre-existing flaws or pinholes in the passivation layer are sites for continuous gallium contact to the underlying Al metal lines.

With a higher ion current density, or higher ion flux, a larger ion dose is deposited on the surface of the passivation layer. Thus charge build-up is increased, and more ions transport down the pinholes or flaws in a given time. The result is a higher occurrence of failure events. With a greater temperature, transport of Ga^+ ions is enhanced. The surface diffusion of Ga^+ ions to and along the defects is a likely way to cause passivation failure, and thus temperature has a notable effect on this thermally activated process. The temperature dependence should follow the Arrhenius relation.

Liquid gallium, through capillary forces in the tight pores, may be formed. The formation of liquid gallium may accelerate the failure process above and beyond normal Arrhenius behavior predictions. Therefore, as the temperature is raised, failure incidence is predicted to increase for a given ion flux, and a greater amount of material is available for surface transport down the pores. Also, more charge

build-up occurs. The result is a higher incidence of failure events during traverse of the ion beam. The interpretation here is only speculative, based on the experimental observation.

It should be noted that the positive gallium ions deposited on the passivation film also cause the build-up of an electric field across the dielectric layer. Therefore, field driven Ga^+ ion transport to the pre-existing defects is a possible scenario, and dielectric breakdown of the passivation film at weak spots may occur. These effects could contribute to the passivation film damage as well. However, the presentation of the data related to the electric-field effects is not the purpose of this investigation.

Above 30°C , liquid-solid transition of gallium occurs. Figure 16 illustrates the statistical variation of the data collected at 25°C and at 30°C ; Error bars are around $\pm 16\%$. It was found that the first standard deviation of these data do not overlap, particularly at the lower ion current densities. Therefore, it is probable that the physical state of gallium may have influence on the failure incidence of the passivation film at or above the solidification temperature of gallium. Whether or not there is influence will depend on the degree of supercooling of liquid gallium required to nucleate solid gallium within the pores.

Figure 16. Statistical data of failure incidence vs. ion current density for temperatures of 25°C and 30°C.

5.3 Effect of Traverse Velocity on the Failure Incidence

Figure 17 shows the passivation film failure incidence as a function of traverse velocity. The experiment was performed on the PSG passivation film at temperatures of 25°C and 35°C and at current density of 1.04×10^{-2} mA/cm² and 3.82×10^{-2} mA/cm². It was found that below the velocity of 4.85 μ m/sec the failure incidence saturates. That is, a failure incidence plateau is observed on the curve. If defects nucleate and grow, they should "pop up" during the entire exposure time, at random; if defects are already there, they only need to be decorated by the Ga⁺ ion charge. They would also be predicted to occur more nearly at the leading edge of the exposure window; and this is observed. The plateau of the curve and leading-edge failure events may indicate that defects pre-exist in the film. That is, they must have been generated during IC processing rather than during FIB exposure.

The above interpretation assumes that the charge build-up on the surface plays a minor role in the damage process. That is, if the charge build-up on the surface due to the impinging Ga⁺ ion flux drives the gallium transport down the defects, then the driving force would be reduced after the first "failure" event. This too would result in a "plateau" in failure incidence at the lower velocities, as shown in Fig. 17. If charge-discharge occurs, however, no more events could be predicted, particularly for the case of dielectric breakdown events.

Figure 17. The influence of traverse velocity on the failure incidence of the passivation film. Data were obtained at temperatures of 25°C and 35°C. Current density $J_1 = 1.04 \times 10^{-2} \text{ mA/cm}^2$, and $J_2 = 3.82 \times 10^{-2} \text{ mA/cm}^2$.

The short circuit caused by the initial event will quench follow-on events.

The data of Fig. 17 in general show that the failure incidence increases as the traverse velocity decreases. At high velocity, insufficient charge and surface collected gallium build up on the passivation film to cause failure events. When the specimen is driven at very low velocity, however, enough Ga^+ ions and charge are collected on the passivation layer to induce failure events. This velocity effect demonstrates that the defects in the passivation layer exist before ion beam scanning. The bombardment of Ga^+ ions does not nucleate and grow the defects.

Figure 17, similar to the data of Figure 15, shows that the failure incidence along the passivation step also depends on the temperature and current density, and therefore, on the ion flux. Increases in temperature and ion flux both lead to a higher number of failure events. The curves in Fig. 17 would also suggest that the reason for the shift in the plateau is mainly due to the time dependence of gallium ion transport down the existing pores. And the information of gallium transport obtained here is totally consistent with the data presented in section 5.6.

5.4 Comparison of Failure Incidences between Various Batches of Wafers

The failure incidence experiment was also conducted on one other patterned wafer with PSG as the passivation film. The two wafers were carefully selected to be from the same vendor, but representing different batches. Figure 18 shows the failure incidence in batch 2 vs. that in batch 1. Batch 1 is the major wafer on which most experiments were performed. From the plot, it was found that the absolute failure incidence in batch 1 is higher than that in batch 2 almost by a factor of two. This finding supports the conclusion that the focused ion beam method may be of great utility to locate the presence of pinholes or flaws in passivation layers and also supports the idea that the flaws are pre-existing, not formed by the ion bombardment.

To test whether the trends observed for the silicon oxide passivation film are consistent with trends observed for other similarly-processed but compositionally different passivation film, failure incidences for silicon nitride passivated wafers were compared at a temperature of 35°C and at a current density of 3.82×10^{-2} mA/cm². The data are shown in Figure 19. Although the passivation films of the two wafers are different, the failure incidences exhibit the behavior of saturation (plateaus in Fig. 19) as the velocity approaches zero. Only the plateau values vary. The

Figure 18. Plot of PSG passivation film failure incidence in batch 2 vs. that in batch 1 (Both batches come from the same vendor).

Figure 19. Comparison of failure incidence as a function of traverse velocity for PSG and silicon nitride passivated wafers.

failure incidence may depend on the type of the passivation film for a given exposure condition, or it may solely be due to a difference in process history. Resolution of the controlling factors is beyond the scope of the current study.

5.5 Effect of Ga⁺ Ion Energy on the Passivation Film Failure Incidence

Figure 20 shows the failure incidence vs. ion flux at ion energies of 20 and 30 keV for two temperatures: 25°C and 35°C. At a constant temperature setting, ion energy has little influence on the passivation film failure incidence. It is known that the mean implantation depth of Ga⁺ ions is a function of ion energy. The above result suggests that implantation depth of Ga⁺ ions does not affect the number of failure events. Additionally, there appears to be sufficient collected charge to promote passivation film failure in both instances. It is the time-dependent decoration of the existing defects with cations that determines the failure incidence during FIB exposure.

Figure 20. The effect of Ga^+ ion energy on the failure incidence of passivation film compared at temperatures of 25°C and 35°C. Ion energy $E_1 = 20 \text{ keV}$, and $E_2 = 30 \text{ keV}$.

5.6 Evaluation of the Activation Energy for Surface Diffusion of Gallium Ions

To test the proposed possible mechanism that surface diffusion of Ga^+ ions to and within the existing passivation film defects is the scenario responsible for failure events, the activation energy of this failure process was determined. The time, t , until a failure event occurs once the Ga^+ ion fluence starts, is called the failure time. This failure time is expected to be inversely proportional to the rate of surface transport of gallium, per the Arrhenius relation. Figure 21 shows the semilog plot of the time-to-failure, t , as a function of inverse, absolute temperature. The linear fit to the data yields an activation energy of 0.26 eV. This value is consistent with the activation energy reported for the surface diffusion of gallium on germanium⁽¹⁴⁾.

5.7 Summary

The damage mechanism which is active during FIB modification of passivated ICs reported here can be summarized as follows. The proposed operative failure mode is the formation of liquid gallium inside pre-existing capillary pores in the passivation film. The calculated activation energy governing the failure process, 0.26 eV, supports the hypothesis that the failure process is controlled by surface diffusion of gallium to and along the defects. The actual

Figure 21. Determination of the activation energy for Ga^+ ion induced failure: semilog plot of the time-to-failure, t , as a function of reciprocal, absolute temperature.

failure event consists of electrical contact of liquid gallium to the underlying aluminum lines and the subsequent electrical discharge which damages the passivation film.

5.8 Future Work

As discussed in the previous sections, positive charge accumulation plays an important role in the passivation film failure. That is, a higher ion flux leads to a greater number of failure events. The manufacturer of the SMI 8300 focused ion beam system has reported that by adding an electron gun "shower" to the system, the degree of passivation film damage could be reduced. Damage is inversely proportional to the ratio of electron beam current to ion beam current. The Ga^+ ions are neutralized during the ion beam scanning when an electron beam is co-incident on the target.

According to the surface charge model, incident positive gallium ions build up on the passivation film and generate an electric field, whose strength depends on the number of accumulated Ga^+ ions. A co-incident electron beam may affect passivation film failure in two aspects. First, neutralization of Ga^+ ions will weaken the electric field and decrease the driving force for Ga^+ ion transport along pre-existing defects. Secondly, the probability of charge induced dielectric breakdown on weak spots (i.e., defects) could be reduced by combining gallium ion neutralization. Both factors would

reduce the tendency for electrical shorting. Thus, the occurrence of electrical shorting would be reduced. Therefore, the electron beam source may be used as a means to sort the "charge" driving force from the Ga^+ ion decoration mechanism. Future studies will be undertaken to examine the effect of an electron shower on the failure incidence of the passivation film.

CHAPTER 6

CONCLUSIONS

In this investigation, a number of interesting observations associated with the passivation film failure of patterned wafers during FIB microsurgery were made. They are as follows:

- (1) The failure events of this study consistently occurred along the steps of metal 1 aluminum lines over the entire temperature range of 15°C to 45°C.
- (2) The failure incidence of the passivation film is temperature-dependent. And the failure process is controlled by the Arrhenius relation. The activation energy of the failure process determined from the experiment appears to be associated with the surface diffusion of Ga^+ ions to and along pre-existing defects in the passivation layer. The measured activation energy of 0.26 eV is in excellent agreement with the reported value of 0.20 eV for surface transport of Ga on Ge.
- (3) Ga^+ ion impingement does not create defects such as pinholes or cracks. These defects are highly process-dependent. The results provide evidence that focused ion beam IC modification causes passivation film damage dependent on the presence of pre-existing defects in the film.

- (4) The comparison of failure incidences from two similar wafer batches from the same vendor suggests that the focused ion beam method can be a powerful defect-finding tool for checking the quality of both the passivation film and dielectrics. This result explores a new application of focused ion beam technology.
- (5) It is rationalized that liquid gallium formation within pores, together with surface diffusion of Ga^+ ions to and along defects, is the possible damage mechanism responsible for the failure of passivation films during FIB IC microsurgery.

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