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論 文 内 容 要 旨

Chapter 1　Introduction

The progress of scaling down in IC has realized the high performance electronic devices. The IC miniaturization increases the density of electrical current in the interconnecting metal lines. Recently, the width of the metal line in the IC has been thinner than 100 nm, and the current density in the line reached about one million ampere per square centimeter ($1MA/cm^2$). The power consumption continues to increase year after year. This means the increase in generation of heat and increase in temperature of the device itself. Thus, the operating condition of IC has been severer from the viewpoint of reliability.

Increases in current density and Joule heating due to scaling down of IC deteriorate the reliability in the metal line. Electromigration might be one of the main damage of the interconnecting metal line and leads to serious deterioration of the IC package reliability. Electromigration is caused by a transportation of metallic atoms in the line by electron wind. The damage induced by electromigration appears as the formation of voids and hillocks. The voids are formed as a result of depletion of metallic atoms and, conversely, the accumulation of atoms results in hillock formation. The growth of voids and linking themselves result in electrical discontinuity in the IC metal lines and lead to open-circuit failure. Therefore, it is significant from the viewpoint of assuring the reliability of IC that the lifetime of the metal line, which is mainly determined by electromigration damage, is predicted quantitatively.

So far, the lifetime under operating condition has been predicted based on the results of the lifetime measurement obtained from the acceleration tests under high current density and high temperature. The data obtained from the acceleration tests are extrapolated to the device-operating conditions by Black's empirical equation. Black's equation has been used widely for lifetime prediction in industry. However, the adequateness of the extrapolation by Black's equation is not sufficient because the prediction result depends on the choice of the condition of acceleration test. Acceleration tests to determine the constants in Black's equation are required for respective line shape. In this

way, the prediction of the metal line's lifetime using Black's empirical equation may not be universal and accurate way in practice. Under these circumstances, in this thesis, the reliability evaluation of electromigration damage was focused on. The development of a practical and universal method for predicting the electromigration damage was attempted.

Chapter 2 Governing Parameter for Electromigration Damage in Passivated Polycrystalline Line

The governing parameter for electromigration damage in a polycrystalline line covered with a passivation layer, AFD^*_{gb}, was formulated considering the effect of the atomic density gradient due to electromigration on the damage mechanism in passivated metal line. A method of deriving film characteristics was also developed based on AFD^*_{gb}. The parameter AFD^*_{gb} was applied to both passivated metal lines and unpassivated ones made of the same Al film. The film characteristics of these lines were experimentally obtained by the AFD^*_{gb}-based method. It was shown that the AFD^*_{gb}-based method was able to reflect the effect of passivation on the atomic diffusion mechanism accurately and to determine both a film characteristic depending on the line-length and also the other film characteristics independent of the line-length appropriately. Furthermore, even in the case of an unpassivated metal line, AFD^*_{gb} was able to reflect the fact that the atomic density gradient is negligible. Therefore, it was able to be concluded that the validity of the film characteristics obtained from the AFD^*_{gb}-based method confirmed the usefulness of the governing parameter AFD^*_{gb}.

Chapter 3 A Method of Reliability Evaluation for Electromigration Failure in Passivated Polycrystalline Line Using the Governing Parameter

A prediction method for electromigration failure in passivated polycrystalline lines was proposed using AFD^*_{gb}. The lifetime and a possible failure site in the passivated polycrystalline line were predicted by means of numerical simulation of the failure process covering the building up of atomic density distribution, void initiation, void growth and ultimately – line failure. In the simulation, the changes in current density and temperature distributions due to void growth were taken into account. The advantage of this method is to predict the failure based on the theory of the electromigration mechanisms, not empirically. And, this method has the capability of universal failure prediction, since it requires only the film characteristics determined from acceleration tests. The usefulness of the method was verified by experiment where two passivated polycrystalline lines with different lengths (Sample L and Sample S) were treated. In the experimental verification, the predicted lifetimes agreed well with the experimental results for two metal lines with different line-lengths. Concerning the location of the failure, the most frequent site in the experiment agreed with the prediction result, though the failure sites experimentally obtained were somewhat spread. The result of the experimental verification in the case of Sample L is shown in Fig.3-17. Thus, it was shown that the present prediction method based on the governing parameter was able to predict both the lifetime and the failure site of the passivated polycrystalline lines accurately.

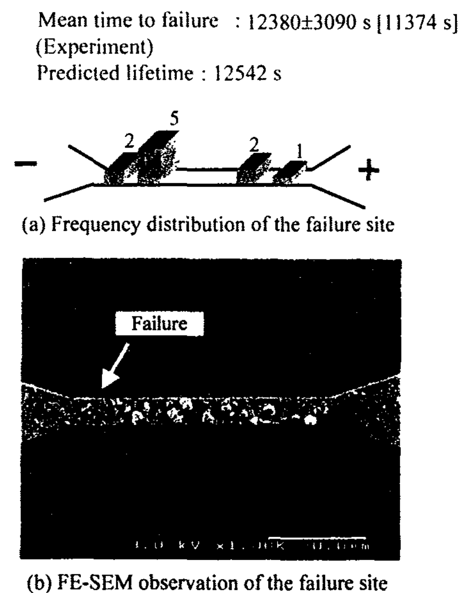

Fig.3-17 Experimental results in the case of Sample L.

Chapter 4 Application of the Evaluation Method for Passivated Polycrystalline Line to Practical Problems

Two applications of the AFD^*_{gb}-based method for reliability evaluation to practical line structures were presented. As the first application, angled polycrystalline lines covered with a passivation layer were treated. Using the AFD^*_{gb}-based method for reliability evaluation, the failures in various angled lines were simulated. Based on the simulation results the dependencies of lifetime and failure location on line-shape were investigated. As the second application, the polycrystalline lines with some kinds of passivation thickness were treated. The effect of passivation thickness on the failure prediction was focused on. Firstly, the failure process in passivated polycrystalline lines was investigated in detail. As the result, the local stress of suppression of the hillock formation was considered as the parameter associated with the effect of the passivation thickness on electromigration damage. Through expressing the local stress by the characteristic constants used in the AFD^*_{gb}-based method for the reliability evaluation of passivated metal lines, the characteristic constants influenced by a passivation thickness were extracted. Secondly, the film characteristic constants depending on the passivation thickness were experimentally determined in the lines with three kinds of passivation thickness. Finally, by extrapolating the obtained dependencies, the characteristic constants in the line covered with the thicker passivation were determined, and the lifetime of these lines was predicted by the reliability evaluation method based on the governing parameter. The dependency of the lifetime on the passivation thickness was evaluated as shown in Fig.4-23. It was shown that the reliability evaluation of metal lines considering passivation thickness was possible and, consequently, determination of an optimum thickness of the passivation for the required lifetime was possible.

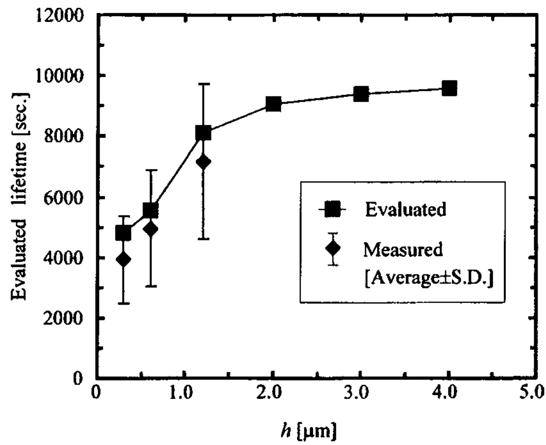

Fig.4-23 The lifetime against passivation thickness, h.

Chapter 5 Application of the Evaluation Method for Passivated Polycrystalline Line to Line Structure without Current Input and Output Pads

At first, a governing parameter for electromigration damage at the ends of passivated polycrystalline line, $AFD^*_{gb}|_{end}$, was expressed considering the boundary condition at the line ends with respect to atomic diffusion. By the way, it is known that the cathode end of the via-connected line drifts in the direction of electron flow as a result of electromigration. The derivation method of the film characteristics using $AFD^*_{gb}|_{end}$ was also presented taking notice of the drift phenomenon. By equating the drift velocity expressed using $AFD^*_{gb}|_{end}$ with experimental one, the film characteristic constants were obtained. Through the discussion on the validity of film characteristics obtained, the adequateness of $AFD^*_{gb}|_{end}$ was verified. Next, the method to evaluate the value of threshold current density, j_{th}, was shown based on the numerical simulation using the governing parameters. It was shown by the simulation, that the atomic density distribution in the line held a steady state without reaching the critical atomic density for damage initiation, N^*_{min}, when input current density, j, was below j_{th}. Also, the simulation showed that the steady atomic density in the line, N^*,

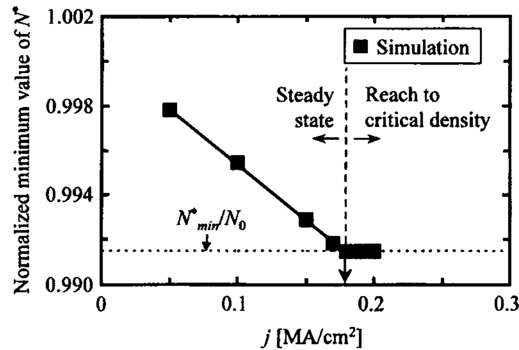

Fig.5-10 Evaluation of the threshold current density.

gradually approaches the critical atomic density for damage initiation with increasing the current density (See Fig.5-10), where N_0 indicates the initial atomic density. Consequently, the simulation with various current densities was able to obtain the threshold current density. And finally, the usefulness of the evaluation method of the threshold current density was shown by observing good agreement between the evaluation result from the numerical simulation (See Fig.5-10) and the experimental one (See Fig.5-11).

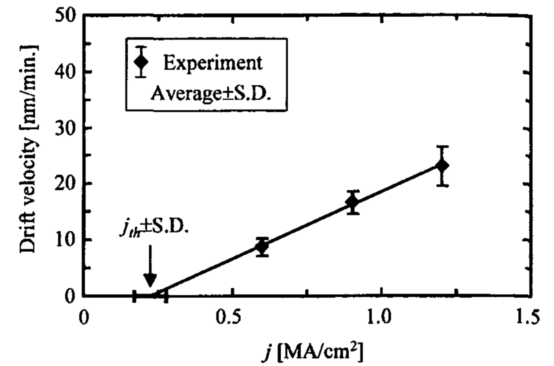

Fig.5-11 Measurement of the threshold current density.

Chapter 6 Governing Parameter for Electromigration Damage in Passivated Bamboo Line

A governing parameter for electromigration damage in the bamboo line covered with a passivation layer was proposed. The formulation was based on the parameter AFD_{li} for unpassivated metal lines. Atomic flux divergence in the covered bamboo line, AFD^*_{li}, was formulated by adding the effect of atomic density gradient to the governing parameter for electromigration damage in uncovered lines, AFD_{li}. Next, the drift velocity in the case of bamboo line was theoretically expressed considering the boundary condition at the line ends with respect to atomic diffusion, i.e. no incoming and outgoing of the atoms at the line ends, where the expressed drift velocity included AFD^*_{li}. The film characteristic constants were determined from the measurement of drift velocity. By equating the theoretical drift velocity with experimental one, the film characteristic constants in AFD^*_{li} were obtained.

Chapter 7 Reliability Evaluation for Electromigration Damage in Passivated Bamboo Line Using the Governing Parameter

The method to evaluate the value of j_{th} in the case of bamboo line was shown based on the numerical simulation using the governing parameter, AFD^*_{li}. The simulation showed that the atomic density distribution gradually built up with time and later held the steady state under the input current density below j_{th}. And also, the simulation demonstrated that the steady atomic density at the line end gradually approaches the critical atomic density for damage initiation with increasing the input current density. Consequently, the simulation with various current densities was able to obtain the threshold current density. And finally, the usefulness of the evaluation method of the threshold current density was shown by observing good agreement between the evaluation result from the numerical simulation and the experimental one. The fact that the evaluation method of the threshold current density was successfully constructed based on AFD^*_{li} concurrently confirmed the adequateness of the governing parameter, AFD^*_{li}.

Chapter 8 Conclusions

This research pioneered the research field of the prediction method of electromigration damage. The approach to prediction method of electromigration damage based on the numerical simulation using the governing parameter is very unique and original work. And, its application to the IC design is expected to be very helpful for industrial field from the reliability point of view. The IC design using the developed prediction method of electromigration damage makes it possible to ensure the reliability of IC products based on the theoretical evidence, not empirically. Therefore, the proposed evaluation method has the capability to bring the higher integration of IC and contributes to the realization of higher performance IC.

論文審査結果の要旨

半導体デバイスの高集積化に伴い、微細化された金属薄膜配線においては高密度電流およびそれに伴うジュール熱の上昇に起因して、エレクトロマイグレーション損傷が問題となっている。エレクトロマイグレーションとは高密度電子流による金属原子の拡散現象のことであり、原子流束が不均一な箇所では原子の局所的な損失あるいは蓄積が生じる。原子の局所的損失はボイドを形成し、ボイドの成長は断線故障を招く。

著者は、エレクトロマイグレーション損傷に影響する因子を統合した当該損傷の支配パラメータを特定し、同支配パラメータを用いた集積回路配線におけるエレクトロマイグレーション損傷の評価法の開発に成功した。本論文はこれらの開発についてまとめたものであり、全編8章よりなる。

第1章は序論である。

第2章では、保護膜被覆多結晶配線におけるエレクトロマイグレーション損傷の支配パラメータの定式化を行っている。保護膜被覆配線と保護膜のない配線に同支配パラメータを適用し、これにより導出された物性値の妥当性を検討することにより、同支配パラメータの有効性を実験的に検証している。これは有益な成果である。

第3章では、第2章で提案の支配パラメータを用いた断線過程の数値シミュレーションに基づいた保護膜被覆多結晶配線の信頼性評価法を開発している。配線寿命、断線箇所を予測し、予測結果と実験結果を比較することにより本信頼性評価法の有効性を検証している。これは有益な成果である。

第4章では、第3章において述べた信頼性評価法を、折れ曲がる多結晶配線の寿命および断線箇所の予測に適用している。さらに保護膜厚さを考慮した配線寿命の予測が可能であることを明らかにしている。これは有益な成果である。

第5章では、ビア接続配線へ本信頼性評価法を展開している。ビア接続配線では、エレクトロマイグレーション損傷が発生する臨界の電流密度、すなわちしきい電流密度が存在する。保護膜被覆多結晶配線を対象に、しきい電流密度の評価方法を開発し、その有効性を実験的に検証している。これは世界に先駆けた成果である。

第6章では、保護膜被覆バンブー配線におけるエレクトロマイグレーション損傷の支配パラメータの定式化を行っている。さらに同支配パラメータを用いて、配線の物性値の導出が可能であることを明らかにしている。これは有益な成果である。

第7章では、第6章で提案の支配パラメータを用いて、保護膜被覆バンブー配線の信頼性評価法を開発し、その有効性を実験的に検証している。これは有益な成果である。

第8章は結論である。

以上要するに本論文は、集積回路配線におけるエレクトロマイグレーション損傷の支配パラメータを特定し、同支配パラメータを用いて配線の信頼性評価法を開発したもので、理論的裏付けに基づいた配線の信頼性確保に貢献するものであり、機械知能工学の発展に寄与するところが少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。