O EFEITO DE CAMADAS DIELÉTRICAS FINAIS DO SILÍCIO NA DINÂMICA DE AQUECIMENTO DE INTERCONEXÃO EM CHOQUE TÉRMICO

THE EFFECT OF THIN DIELECTRIC LAYERS AT SILICON ON INTERCONNECTION HEATING DYNAMICS AT THERMAL SHOCKS

ВЛИЯНИЕ ТОНКИХ ДИЭЛЕКТРИЧЕСКИХ СЛОЕВ НА КРЕМНИИ НА ДИНАМИКУ НАГРЕВА МЕЖСОЕДИНЕНИЙ В УСЛОВИИ ТЕПЛОВЫХ УДАРОВ

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RESUMO

A relevância do estudo se deve ao fato de que, nas condições de desenvolvimento da micro e nanoeletrônica, é necessário prestar atenção aos sistemas de comutação resistiva, que são a base nas estruturas dessas áreas da eletrônica. O trabalho trata da investigação do papel de finas camadas dielétricas de óxido e nitreto de silício na dinâmica de aquecimento de interconexão em placas monocristalinas de silício. O método principal para o estudo desse problema é o método do experimento, que permite identificar as características da influência da subcamada dielétrica nos regimes térmicos de sistemas multicamadas. É mostrado que a passagem de pulsos de corrente (amplitude de até $6 \cdot 10^{10}$ A/m² e uma duração de até 600 μ s) leva a danos térmicos das interconexões até a interrupção do circuito elétrico. A natureza da destruição depende fortemente da qualidade da deposição de filmes dielétricos e metálicos, bem como do estado da interface metal-dielétrica. Verificou-se que os oscilogramas da inclusão, obtidos durante a passagem de um pulso de corrente, refletem claramente a mudança nos parâmetros dimensionais (h_2) e térmicos (λ_2) das subcamadas dielétricas; foram considerados os mecanismos de degradação térmica dos sistemas de metalização de alumínio com subcamadas dielétricas finas relacionadas à sua fusão; verificou-se que a formação de zonas fundidas está relacionada à redução local da seção transversal do filme e, conseqüentemente, ao aparecimento de uma zona fundida que se coagula em quedas no curso da corrente de pulso e promove a interrupção do circuito elétrico. O método proposto pode ser aplicado para avaliar as propriedades térmicas de filmes finos de dielétricos.

Palavras-chave: comutação resistiva, interface metal-dielétrico, estrutura para altas temperaturas.

ABSTRACT

The relevance of the study is due to the fact that in the conditions of development of micro-and nanoelectronics, it is necessary to pay attention to resistive switching systems, which are the basis in the structures of these areas of electronics. The work deals with the investigation of the role of thin dielectric layers of silicon oxide and nitride on interconnection heating dynamics at monocrystalline silicon plates. The leading method to the study of this problem is the method of experiment, which allows identifying the features of the influence of the dielectric sublayer on the thermal regimes of multilayer systems. It is shown that passage of current pulses (amplitude up to $6 \cdot 10^{10}$ A/m² and duration up to 600 μ s) leads to thermal damage of interconnections right up to breaking the electric circuit. The character of destruction strongly depends on the quality of deposition of dielectric and metal films as well as on the state of the dielectric-metal interface. It was found that the oscillograms of the inclusion, taken during the passage of a current pulse, clearly reflect the change in the dimensional (h_2) and thermal (λ_2) parameters of the dielectric sublayers; considered the thermal degradation mechanisms of the aluminum metallization systems with thin dielectric sublayers related to its melting; it was found that formation of

melted zones is related to local reduction of film cross-section and consequently to the appearance of a melted zone that coagulates into drops in the course of current pulse passing and promotes breaking the electric circuit. The proposed method can be applied to assess the thermal properties of thin films of dielectrics.

Keywords: *resistive switching, metal-insulator interfaces, structure for high temperature.*

АННОТАЦИЯ

Актуальность исследования обусловлена тем, что в условиях развития микро- и наноэлектроники необходимо уделять внимание резистивным коммутационным системам, которые являются основой в структурах этих областей электроники. Работа посвящена изучению роли тонких диэлектрических слоев оксида и нитрида кремния на динамику нагрева межсоединений на пластинах монокристаллического кремния. Ведущим методом к исследованию данной проблемы является метод эксперимента, позволяющий выявить особенности влияния диэлектрического подслоя на тепловые режимы многослойных систем. Показано, что прохождение токовых импульсов амплитудой до $6 \cdot 10^{10}$ А/м² и длительностью до 600 мкс приводит к тепловому разрушению межсоединений вплоть до обрывов электрической цепи. Характер разрушений сильно зависит от качества нанесения диэлектрической пленки и пленки металла, а также состояния межфазной границы диэлектрик-металл. Обнаружено, что осциллограммы включения, снимаемые в процессе прохождения импульса тока, четко отражают изменение размерных (h_2) и тепловых (λ_2) параметров диэлектрических подслоев; рассмотрены механизмы тепловой деградации систем алюминиевой металлизации с тонкими диэлектрическими подслоями, связанные с её оплавлением; выявлено, что образование участков расплава связано с локальным уменьшением поперечного сечения пленки и, как следствие, появлению расплавленного участка, который в процессе прохождения импульса сворачивается в капли и способствует обрыву токопроводящей линии. Предложенная методика может быть применена для оценки тепловых свойств тонких пленок диэлектриков.

Ключевые слова: *резистивное переключение, интерфейс металл-диэлектрик, структура для высоких температур.*

1. INTRODUCTION

It is well known that the resistive commutation systems (along with p-n junctions) are the key elements in the micro- and nanoelectronic structures (Shejko *et al.*, 2016; Ambrogio *et al.*, 2017; Shejko *et al.*, 2017; Iskovych-Lototsky *et al.*, 2019). This fact is related to a large extent to the constant tendency to structure miniaturization (Bermejo *et al.*, 2016; Long *et al.*, 2016) (which correspondingly results in increasing "thermal" loads on them), as well as requires structure operation speed (Hofmann *et al.*, 2004)

In this connection much attention is being given to metal-insulator-semiconductor structures and physical-mechanical processes that are basic to their operation: solid-state reactions at interfaces (Popok *et al.*, 2016; Dornic *et al.*, 2018; Pichkur *et al.*, 2015), diffusion and aggregation of complexes, generation-recombination processes of charge carriers (Woïrgard *et al.*, 2015; Brincker *et al.*, 2018), problems of heat conduction in multilayer media (Skvortsov *et al.*, 2016a; Hu *et al.*, 2012) and other transport phenomena (van Soestbergen *et al.*, 2010; Nguyen *et al.*, 2011; Hadała *et al.*, 2011).

It is also known that a semiconductor crystal is subjected to high thermoelastic stresses in the power of electronic devices, especially under the pulsed operating conditions (Gavryushin *et al.*, 2018a; Gavryushin *et al.*, 2018b). In this case, the metallization systems, contacts, and near-contact areas of a semiconductor structure are the most "vulnerable", because they have many interfaces and geometrical heterogeneities (Orlov *et al.*, 2003b; Skvortsov and Karizin, 2012; Skvortsov *et al.*, 2016a; Ruffilli *et al.*, 2017;). Therefore, the purpose of the present work is an investigation of the effect of thin dielectric layers on the heating dynamics of interconnections on silicon under a surface thermal shock.

2. MATERIALS AND METHODS

In this work, the metal-semiconductor and metal-dielectric-semiconductor structures were studied. The monocrystalline silicon plates oriented in the (111) and (100) directions served as substrates. They were doped with phosphorus (it is the intentional introduction of impurities into an intrinsic semiconductor for the purpose of modulating its electrical, optical and structural properties); their resistivity varied in the

$\rho = 1 \dots 0.01 \text{ } \Omega \cdot \text{cm}$ range. When studying the Al-Si binary systems, a $30 \dots 50 \text{ } \mu\text{m}$ *n*-epitaxial layer was deposited on some plates to prevent current flow through the semiconductor. Thin silicon oxide SiO_2 or silicon nitride Si_3N_4 films were deposited on some plates to compare temperature dependencies of λ_2 values. Aluminum (as the most popular metallization material in semiconductor structures) served as the conductive metal film (Beshajova and Martin, 2018). Registration of temperature changes in a thin-film structure was made using a test structure as a metallization track. Square current pulses were passed through it, with registering voltage drop $U(t)$ from a part of the test structure. From the $U(t)$ oscillograms, one can judge the dynamics of system heating in the course of current pulse passing. Moreover, the processes of irreversible degradation related to the appearance of melted regions in the structure are clearly reflected in the $U(t)$ oscillograms. It was established that a potential-jump in the $U(t)$ curve is definitely related to the appearance of melted Al fragments on the region analyzed.

Silicon nitride films were prepared using pyrolytic deposition of dichlorosilane with ammonia onto silicon plates at reduced pressure ($\sim 50 \text{ Pa}$) in the temperature range of $700\text{--}900^\circ\text{C}$. Deposition of silicon nitride films was realized at a specialized plant (Figure 1). It involved a quartz reactor (a quartz tube 100 mm in diameter (1, Figure 1) with a temperature-controlled zone), afore vacuum evacuation system (operating in the continuous mode with pump speed to 30 l/s) and a working gas (monosilane SiH_4 and ammonia NH_3) feed system. A diffusion furnace provided a uniform temperature of operating zone at a length of 700 mm with an accuracy of $\pm 2^\circ\text{C}$.

The thermal oxide was grown in diffusion furnaces using the standard technology (Birouk and Madi, 2011) in the temperature range of $1150\text{--}1250^\circ\text{C}$ in dry oxygen. A number of specimens a to isothermal annealing at 550°C in the inert atmosphere to stabilize contact properties and improve adhesion. The process of silicon thermal oxidation in oxygen or water vapor is usually described with resulting chemical reactions (Equations 1 and 2).

The films of thermal silicon oxide were grown in a flow reactor with vertical plates (Figure 2) in "dry" oxygen (O_2) and in "wet" oxygen – with the presence of water vapor ($\text{O}_2 + \text{H}_2\text{O}$).

A choice of oxidation method was determined by the required thickness and properties of the formed oxide. The required thin

(< $0.5 \text{ } \mu\text{m}$) oxide films were grown in dry oxygen. To this end, the boats with plates (2, Figure 2) were gradually moved into the furnace heated to $800\text{--}900^\circ\text{C}$. To prevent substrates warping, the temperature was gradually raised to the required value ($900 - 1200^\circ\text{C}$) and was supported in the course of oxidation with an accuracy of $\pm 1^\circ\text{C}$. After completing the oxidation process, the temperature in the furnace was gradually reduced, and the substrates were taken out.

The formation of test structures was performed with optical photolithography (Figure 3, a-d). The investigation of test structures was made using the voltmeter-ammeter method from the electrical response taken from different structure areas in the passage of single current pulses of different forms (Skvortsov *et al.*, 2018; Skvortsov *et al.*, 2016b). The experimental investigation of degradation processes was performed for the test structures (Figure 3, e) from the switching oscillograms $U(t)$. They were taken by the appropriate probes in the course of current pulse passage and were recorded with a digital oscillograph.

The temperature dynamics of metallization track $T_1(t)$ was calculated from the variation of voltage drop $U(t)$ (Equation 3).

Here $R_0 = 0.88 \text{ } \Omega$ is the metallization track resistance at $T_0 = 290 \text{ K}$ measured with the voltmeter-ammeter method; $\alpha = 0.0043 \text{ K}^{-1}$ is the aluminum temperature coefficient of resistance. The metallographic studies of the results of degradation processes were performed using a digital optical 3D microscope Keyence VHX6000.

3. RESULTS AND DISCUSSION:

It was noted that the temperature variations of the structures under investigation were judged from the switching oscillograms. Figure 4 presents the typical results of these investigations for systems with a dielectric SiO_2 sublayer. The obtained curves are described by known Equation 4 (Orlov *et al.*, 1996).

Here and further the indices "1", "2" and "3" apply, correspondingly, to the aluminum metallization, dielectric sublayer, and semiconductor substrate; h is thickness; λ is thermal conductivity; c , d and a are, correspondingly, thermal capacity, density, and thermal conductivity.

Because all the parameters depend on temperature, so as before (Orlov *et al.*, 2003a), we used their temperature-averaged values to calculate T_1 . To this end, the studied temporal

interval was divided into small time intervals Δt . The averaged value of each parameter was calculated as the average integral value taken by it in all elementary intervals. (E.g., the average integral value of b is Equation 5). One can see from Equation 4 that the structure heating dynamics depends on the current strength and parameters of the semiconductor matrix, as well as on thermal conductivity and thickness of the intermediate dielectric film.

The thickness of dielectric sublayer strongly influences the thermal conditions of multilayer systems (see Figure 4). To illustrate, changing the intermediate film thickness h_2 of silicon oxide from 0.1 μm to 0.16 μm increases temperature T_1 of Al film from 390 K to 440 K at $t = 400 \mu\text{s}$ from the moment of pulse switching (Figure 4, dashed line). This leads to an earlier structure overheating: at the same current density $j = 5.5 \cdot 10^{10} \text{ A/m}^2$, the thicker is the intermediate semiconductor layer, the quicker is metallization tracks warm-up (Figure 4).

The presence of dielectric sublayers with different λ_2 values is also clearly represented on oscillograms at the passage of current pulses. There is a big difference between the heat-conducting properties of silicon oxide films and silicon nitride films at different temperature modes of metal layers operation when passing current pulses of the same electric power. This is clearly shown in Figure 5.

Thus the switching oscillograms clearly represent a variation of the dimensional (h_2) and thermal (λ_2) parameters of sublayers. Using the experimental switching oscillograms and the data on thicknesses of dielectric films, we calculated the temperature dependences of λ_2 values for the studied SiO_2 and Si_3N_4 films from the following Equation 5.

The results of the calculations from Equation 6 are presented in Figure 6.

It can be observed that the obtained results agree well with the known literature data for films of silicon oxide (Zhu *et al.*, 2018; Gu and Wang, 2018) and silicon nitride (Fong *et al.*, 2016). Thus the proposed procedure can be applied to estimate thermal properties of thin dielectric films.

Earlier (Skvortsov *et al.*, 2018; Skvortsov *et al.*, 2016a) we revealed that, at high-power electric pulses (pulse duration $\tau \sim 500 \mu\text{s}$ and pulse power $P_i = 5 \dots 17 \text{ W}$), the degradation processes in the binary metallization systems are related to formation of a melted zone (when the

metal melting temperature is achieved) and contact melting processes that occur at the metal-semiconductor interface.

Contrary to the Al-Si systems, the presence of thin dielectric films on semiconductor surface prevents the processes of contact melting in the metal-semiconductor system. Therefore, the beginning of the degradation processes is related solely to Al melting. It is accompanied by an abrupt potential-jump $U(t)$ at the oscillograms followed with its oscillation and a jump related to conducting channel breakdown. Growth of current density to the $j \sim 8 \cdot 10^{10} \text{ A/m}^2$ values appreciably promotes complete melting of the test structure (Figure 7).

Formation of melted zones has been discussed earlier (Brincker *et al.*, 2018). We ascribed this to the processes of electric transfer and thermal diffusion in the defective areas of metal track. Local reduction of film cross-section leads to an increase of current density and consequently to the appearance of a melted zone. In this case, melted metal coagulates into drops, and the conducting line breaks. Results should be presented concisely. Also, point out the significance of the results and place the results in the context of other work and theoretical background.

4. CONCLUSIONS:

It was considered the effect of thin dielectric layers of silicon oxides and silicon nitrides on heating dynamics of interconnections at monocrystalline silicon plates using the oscillographic method. It was found that the switching oscillograms taken in the course of current pulse passing clearly reflect the variation of the dimensional (h_2) and thermal (λ_2) parameters of dielectric sublayers. Using the experimental switching oscillograms and the data on the thicknesses of dielectric films, we calculated the temperature dependences of the SiO_2 films and Si_3N_4 films studied. This proved that the proposed method could be applied to assess the thermal properties of thin films of dielectrics.

It was also shown that passage of current pulses with amplitude up to $6 \cdot 10^{10} \text{ A/m}^2$ and duration up to 600 μs results in thermal damage of interconnections right up to breaking the electric circuit. We considered the thermal degradation mechanisms of the aluminum metallization systems with thin dielectric sublayers related to its melting. It was found that

formation of melted zones is related to local reduction of film cross-section and consequently to the appearance of a melted zone that coagulates into drops in the course of current pulse passing and promotes breaking the electric circuit.

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$$U(t) = I(t)R_0[1 + \alpha(T_1(t) - T_0)] \quad (\text{Eq. 3})$$

$$T_1 = T_0 + \frac{I^2 \bar{R}_1}{S} \left(\frac{h_2}{\bar{\lambda}_2} + \frac{1}{\bar{c}_3 \bar{d}_3} \sqrt{\frac{t}{\bar{a}_3}} \right) \quad (\text{Eq. 4})$$

$$\bar{b} = \frac{1}{\Delta T} \int_{T_0}^{T_1} b(T) dT \quad (\text{Eq. 5})$$

$$\bar{\lambda}_2 = \frac{h_2}{\left(\frac{\Delta T_1 \cdot S}{I^2 \bar{R}_1} - \frac{1}{\bar{c}_3 \bar{d}_3} \sqrt{\frac{t}{\bar{a}_3}} \right)} \quad (\text{Eq. 6})$$

Figure 1. Diagram of installation for deposition of pyrolytic silicon-based films: 1 – quartz reactor, 2 – boat for silicon plates 76 mm in diameter, 3 – vertical silicon plates, 4 – resistance heater, 5 – compactors

Figure 2. Diagram of installation for growth of thin silicon oxide films: 1 – quartz reactor, 2 – boat for silicon plates 76 mm in diameter, 3 – vertical silicon plates, 4 – resistance heater providing temperature in the isothermal zone to 1200 °C

Figure 3. Photographs of a 76 mm silicon plate (a) with a sprayed aluminum film (b), a working photomask (c) and a silicon plate after structures formation (d). A 3D model of a metal film-semiconductor plate test structure (e) to study temperature modes of metallization tracks: I – current area, 1-12 – contact areas to record oscillograms

Figure 4. Switching oscillograms taken from an area of the Si-SiO₂-Al system test structure at passage of a single current pulse (amplitude of $5.5 \cdot 10^{10}$ A/m²) at different thicknesses of dielectric sublayer: 1 – $h_2 = 0$; 2 – $h_2 = 0.1$ μm; 3 – $h_2 = 0.16$ μm; $h_1 = 2.5$ μm. The pulse duration of 450 μs

Figure 5. Switching oscillograms of a Si-dielectric-Al system at the passage of a single current pulse (amplitude $j = 3 \cdot 10^{10}$ A/m², duration 450 μs); $h_1 = 5$ μm, $h_2 = 0.1$ μm: 1 – $h_2 = 0$; 2 – Si₃N₄; 3 – SiO₂

Figure 6. Results of calculation of temperature dependences of $\bar{\lambda}_2$ for SiO₂ films (1) and Si₃N₄ films (2): ● – the experimental data for SiO₂ films from (Zhu et al., 2018; Gu and Wang, 2018), ♦ – those for Si₃N₄ films from (Fong et al., 2016)

Figure 7. Photograph of melting fragment of an Al-SiO₂-Si test structure after the passage of a square current pulse (amplitude $j = 8 \cdot 10^{10} \text{ A/m}^2$ and duration $\tau = 500 \mu\text{s}$)