PVD Aluminium Nitride as Heat-Spreader in IC Technology

L. La Spina, H. Schellevis, N. Nenadović, S. Milosavljević, W. H. A. Wien, A. W. van Herwaarden,
and L. K. Nanver

***Abstract* — A physical-vapour-deposition (PVD) of AlN thin films is presented in this paper. For AlN layers that are $0.8\ \mu\text{m}$ thick, the electrical resistivity is found to be higher than $10^{13}\ \Omega\cdot\text{cm}$, the dielectric constant about 8, and the thermal conductivity around $11\ \text{Wm}^{-1}\text{K}^{-1}$. The deposition conditions are tuned to reduce the stress, to avoid his detrimental effects on integrated devices.**

***Index Terms* — Aluminium nitride, heat spreader, physical-vapor-deposition, reactive sputtering, thin films.**

I. INTRODUCTION

IN advanced silicon integrated circuits (ICs), such as high-frequency (hf) Si/SiGe BiCMOS circuits, heat generation is one of today's major yield killers. In semiconductor industry, the efforts are constantly directed toward the reduction of the minimum feature size, increasing, at the same time, the speed of devices. This means that, in the future, the self-heating and thermal coupling will become enormous due to both the high packing and power densities. Failures due to thermal effects of the transistors will also pose a limit on the individual device performance [1]. For hf devices, where the use of aggressive isolation techniques guarantees the speed performance, new electrical insulators with high thermal conductivity are needed to enhance heat spreading and heat sinking. In order to meet the requirement to produce high quality layers with as high as possible thermal conductivity k_{TH}, different materials have been investigated in the past. The most commonly used dielectrics in silicon technology are oxides and nitrides, but they have very low k_{TH} around $1-3\ \text{Wm}^{-1}\text{K}^{-1}$. For high k_{TH}, the wide band-gap materials such as diamond, silicon carbide (SiC) and aluminum nitride (AlN) have been recently considered.

Aluminium nitride is one of the most versatile III-V compounds, it possesses a large energy band-gap of about 6 eV [2], [3] and several authors focused on properties of AlN thin films for electronics, opto-electronics, and acoustic applications. In particular, due to its electrical and thermal properties, AlN can be used for heat spreading/sinking in IC applications. AlN is a material that is neither contaminating nor poisonous, differently from other materials, such as beryllia for example, and can be both deposited and etched by means already available in conventional silicon processing.

In this work, physical-vapor-deposited AlN thin films are developed. The deposition parameters are tuned to guarantee low stress, high thermal conductivity and electrical insulation. Deposited layers are experimentally characterized using test structures designed for this purpose.

II. FABRICATION PROCESS

A. Deposition Technique

Depending on the desired applications, AlN can be grown using a large variety of techniques: gas source molecular beam epitaxy, reactive molecular beam deposition (RMBD), chemical vapor deposition (CVD), reactive sputtering [4]-[7], etc. However, the most diffused methods are the CVD and the PVD. One important advantage of using PVD is the possibility to deposit films at temperatures substantially lower than in the case of CVD [6], [8]. Indeed the high processing temperature often results in the inclusion of impurities, or leads to the generation of interface defects and cracking. Moreover, the temperature of the deposition is limited by the total thermal budget constrains of microelectronic devices fabrication (e.g. dopant diffusion, melting point of metallization, etc.).

In this work, the aluminium nitride film is deposited by reactive magnetron pulsed-DC sputtering, in a Trikon Sigma sputter machine, with a pure Al target. For AlN layers of less than 1 μm thick, a pulsed-DC power of 2 kW with a pulse width of 1616 ns and a frequency of 250 kHz is used. The substrate temperature is 300 °C and the pressure 5.0 mtorr. Nitrogen incorporation is achieved with a N_2 flow of 75 standard cubic centimeters per minute (sccm) and an argon flow of 38 sccm. No RF bias is applied and the tooling factor is $169\ \text{Å}\,\text{min}^{-1}\text{kW}^{-1}$, where the tooling factor is defined as the deposition speed over the applied power.

For AlN layers of more than about 1 μm thick the stress can lead to cracking. To avoid this, the layer is built up of alternating 0.2-μm-thick layers, the one being deposited with

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L. La Spina (corresponding author), H. Schellevis, N. Nenadović, S. Milosavljević, W. H. A. Wien, and L. K. Nanver are with Laboratory of Electronic Components, Technology & Materials ECTM, DIMES, Delft University of Technology, P. O. Box 5053, 2600 GB Delft, The Netherlands. Email: l.laspina@dimes.tudelft.nl. Phone: +31-15-2782185; fax: +31-15-2787369.

A. W. van Herwaarden is with Xensor Integration, P.O. Box 3233, 2601 DE Delft, The Netherlands.

the parameter set given above and the other deposited with the same parameters except for the addition of a 20 W RF biasing. In this manner it is possible to deposit up to 4-μm-thick AlN layers.

B. *Etching*

The deposited AlN can be etched by a wide range of wet etchants, some typical etch rates of which are listed in Table 1. Even the development step for photoresist patterning will remove about 40 nm of AlN.

For the dimensional control of window etching in AlN layers, however, dry etching in Cl_2/HBr chemistry is very much to be preferred. This is performed in a Trikon Omega etcher. Resist masking is not always attractive for AlN layers that are no more than 2 μm thick because the etch rates of resist and AlN are 306 nm/min and 188 nm/min, respectively, i.e. the selectivity is 1.6:1. Note that it is possible to etch AlN directly on Al by using the same Cl_2/HBr chemistry with endpoint detection. However, since the chemistry used for AlN etching is similar to that of Al etching, the process window for overetching the AlN layer is in reality too small. A greatly improved control of the etching of the 2-μm-thick AlN layers is achieved if it is possible to land on silicon dioxide. In this case, endpoint detection can be accomplished if the area of exposed oxide is more than about 30%. The etch rate of the oxide is 68 nm/min. As drawbacks it has been found that, using a thick layer of resist of 5 μm, the surface of the oxide after AlN etching was rough, as clearly observed from visual inspection.

TABLE 1.
ETCH RATES OF AlN FOR DIFFERENT WET ETCHANTS.

SOLUTION	TEMP [°C]	ETCH RATE [nm/min]
0.55% HF	20	5.6
BHF 1:7	20	13.5
CrO_3/H_3PO_4	70	60

III. MATERIAL PROPERTIES

A. *Stress Measurements*

The high residual stress often observed in AlN thin films appeared to be an obstacle to integration. For this reason the film should exert a minimum stress on the underlying substrate. To manipulate the stress of the AlN layers some effect can be achieved by varying the frequency, pulse width and/or temperature of the deposition. Table 2 shows the stress measured for two different conditions of deposition. The measurements are performed through a Flexus thin-film stress meter. A reduction of the stress is obtained by switching on the RF bias (layer A). The influence on the stress of a heating treatment after the deposition of the aluminum nitride is depicted in Fig. 1.

Without biasing, the layers will produce a tensile stress. Thus, for a thickness of 800 nm a stress of 400 MPa results, while applying a bias of 20 W gives a compressive stress of -500 MPa . By alternatively switching the bias on and off as described in section II.A, a 2-μm-thick layer can be grown with a tensile stress of about 250 MPa. For thicker layers this stress level remains the same and it has been possible to grow good quality layers. If no RF bias is applied the layers will show cracking even for a thickness of 1.6 μm. The layers grown under the alternating bias conditions are robust in this respect and can be used for further processing. However, for a thickness of 3 μm or more, the strain can become so large that significant wafer bowing results and not all process equipment will accept the wafer. At present it is possible to deposit thick layers with very low stress levels that do not give excessive wafer bowing. These layers have, however, not yet been integrated in transistor runs. The stress in AlN films and its dependence on other parameters, as e.g. the temperature of the deposition, the pressure, the fraction of argon flow-rate in the Ar/N_2 mixture, target voltage and so on, have also been investigated by other authors [9]-[14].

TABLE 2.
DEPOSITION PARAMETERS AND RESULTING MATERIAL PROPERTIES OF TWO DIFFERENT PVD AlN LAYERS. THE STRESS VALUES REPORTED HERE ARE TENSILE.

	LAYER A	LAYER B
FREQ. [kHz]	250	DC
PULSE WIDTH [ns]	1616	-
DUTY CYCLE [%]	40.4	100
STRESS [MPa]	+407	+574
d_{AlN} [nm]	836	845
n_f (λ=365 nm)	2.17	2.20
n_f (λ=633 nm)	2.12	2.13

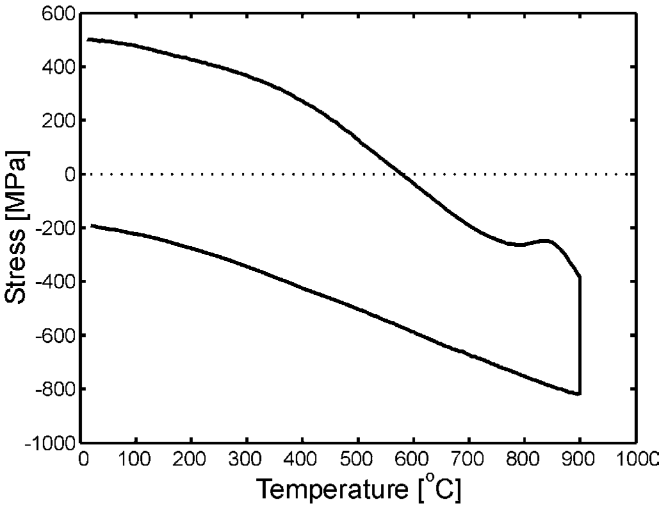

Fig. 1. Stress versus the temperature during the heating-up, cooling-down of 800-nm-thick AlN layer deposited at 300 ºC.

B. *Electrical Properties*

The electrical properties of bulk AlN are typically those of an insulating material. The electrical resistivity for the AlN substrates is, depending on the process technology, between $4\times10^{11}\ \Omega\cdot\mathrm{cm}$ [15] and $5\times10^{13}\ \Omega\cdot\mathrm{cm}$ [16]. The electrical resistivity of aluminium nitride in thin film form was measured in [2] to be in the order of $10^{11}\ \Omega\cdot\mathrm{cm}$.

The deposited AlN thin film, investigated in this work, has clearly a granular structure. The first few nanometers are deposited as an amorphous layer that is the seed for the subsequent polycrystalline growth in vertically elongated grains as seen in the TEM image shown in Fig. 2. The electrical properties are strongly influenced by the grain structure and can have directional dependencies. In order to measure the vertical and lateral electrical resistivity of the deposited AlN, appropriate structures, depicted in Fig. 3, were designed. For extraction of the vertical resistivity, several Al-AlN-Al capacitors, with different aluminium nitride thickness, were fabricated and characterized (see Fig. 3(a)). I-V measurements were performed on the structures and the leakage current in the material versus the applied voltage is given in Fig. 4. The measured electrical resistivity is in the order of $10^{12}-10^{14}\ \Omega\cdot\text{cm}$, depending on the thickness of the material. As can be seen in Fig. 5, the resistivity decreases when the thickness of the material increases. Further experiments are being performed at the moment, in order to clarify the origin of such behavior.

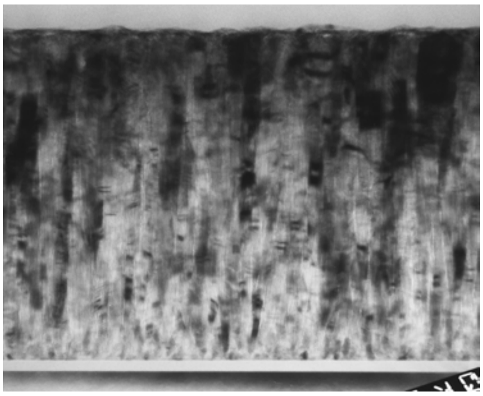

Fig. 2. TEM image of a 2-μm-thick AlN layer deposited on 100 nm thermal oxide.

To extract the lateral conductivity of the AlN layers, multifinger metal structures with a wide range of pitches and metal thickness were fabricated and covered with AlN layers of a thickness up to 0.8 μm. To avoid hillocks formation during thermal processing of the first Al layer, this layer was capped by a 100-nm-thick TiN layer. The lateral resistivity was extracted using the four probes method and found to be higher than $10^{11}\ \Omega\cdot\text{cm}$.

The measured dielectric constant of the AlN layers is about 8 at 1 MHz. Our values are in agreement with the results reported by other authors [8], [17]-[21] that found values in the range of $7-10.4$. As comparison, note that the dielectric constant is 3.9 for SiO_2, which is one of the most common insulating materials employed in microelectronics field, and is 6.5 and 7.9 for SiN and Al_2O_3 respectively [22].

C. Optical Properties

The refractive index, measured at two different wavelengths on the Sopra ES4G ellipsometer, is given in Table 2 for two AlN layers, deposited in different conditions, and it is seen to be about 2.1 - 2.2. These high values indicate a good crystalline rather than amorphous quality of the layers [23]. Furthermore this value is in agreement with the results given in [2], [7], and [24].

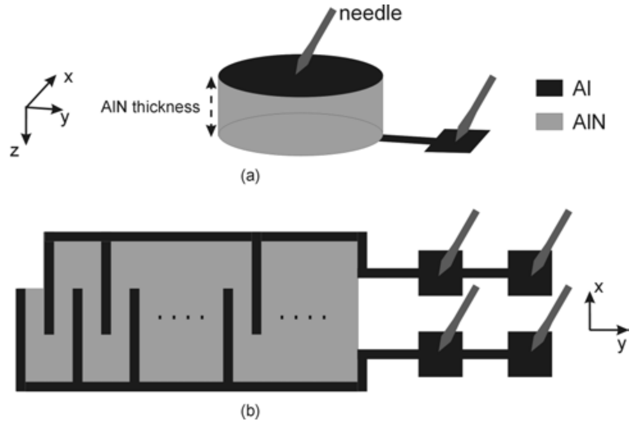

Fig. 3. Test structures employed to extract: (a) the vertical resistivity (3D view), and (b) the lateral resistivity (top view) of the aluminium nitride film.

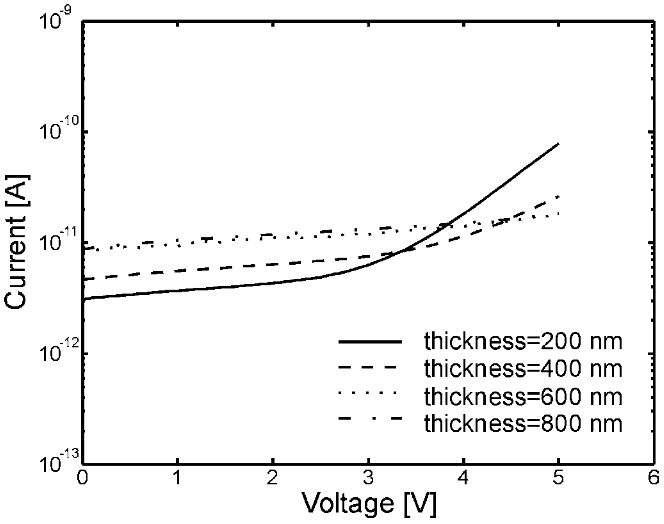

Fig. 4. Current through AlN thin films as a function of applied voltage for different thickness.

D. Thermal Properties

The thermal conductivity of bulk materials can be strongly different from that one of the corresponding thin film. The AlN has a theoretical thermal conductivity k_{TH} of $320\ \text{Wm}^{-1}\text{K}^{-1}$ [25], while the maximum experimental value for the bulk material is $270\ \text{Wm}^{-1}\text{K}^{-1}$ [26]. However, the k_{TH} of AlN film is much lower, in the range of $0.4-26\ \text{Wm}^{-1}\text{K}^{-1}$ [27], [28], since it depends on the deposition process details, grain size and shape, film thickness and impurity concentration. In the present work, the value of the thermal conductivity of AlN film is extracted from a dedicated test structure [29], and it is around $11\ \text{Wm}^{-1}\text{K}^{-1}$. This value is relatively high compared with other materials used in IC technology. For example, the silicon dioxide SiO_2 has a k_{TH} of about $1.4\ \mathrm{Wm^{-1}K^{-1}}$, and the silicon nitride film has a value in the order of $1.5-2\ \mathrm{Wm^{-1}K^{-1}}$ [30], [31].

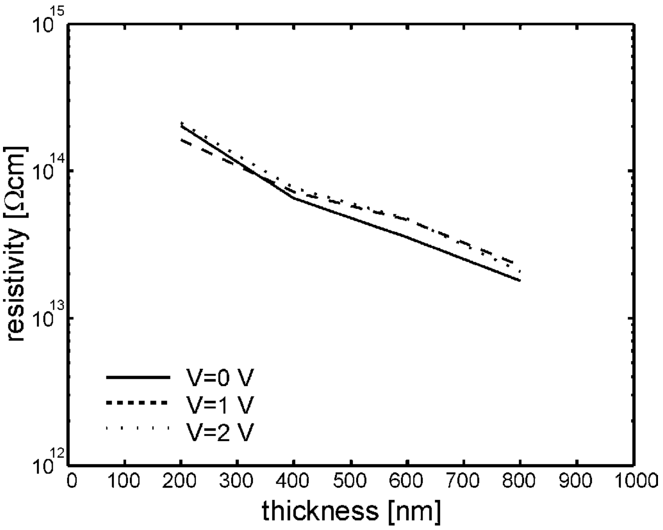

Fig. 5. Resistivity as a function of the thickness of the AlN film at different applied voltages.

IV. CONCLUSION

Deposition conditions have been developed for which good quality aluminium nitride films have been achieved. Compared to previous approaches [10], this technique is also favorable with respect to the thickness of the layers, since it allows deposition of almost stress-free layers. The good dielectric and thermal properties of AlN layers suggest that such material is a candidate to be used as heat spreader in silicon integration processes. The mechanical stress is a point of concern and has prevented, until now, the integration of layers thicker than 2 µm in IC technology.

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