Calibration of MEMS-Based Test Structures for Predicting Thermomechanical Stress in Integrated Circuit Interconnect Structures

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***Abstract*—This paper uses a rotating-beam−sensor structure to show that the extrinsic stress from the mismatch in expansion coefficient between the aluminum and the silicon substrate dominates over the compressive stress from the sputter growth. Sintering the layers at temperatures above 150 °C reduces this compressive stress due to the action of creep. Calibration of the rotation of the device has been undertaken by direct comparison to high resolution X-ray-diffraction measurements and these show that the sensor has a resolution better than 2.8 MPa. Furthermore, we have used the sensor to investigate the variation of in-plane stress with the compliance of the intermetal dielectric, by directly comparing sensors fabricated on SiO_2 and polyimide layers.**

***Index Terms*—Integrated-circuit reliability, interconnect, metallization, reliability, stress.**

I. Introduction

X-RAY DIFFRACTION is the most widespread, nondestructive technique for the determination of stress in thin layers. However, its effectiveness in the measurement of stress in sputtered aluminum films for interconnect features is limited by the highly textured surface of the films and their thickness. This is further complicated by the small lateral dimensions required to meet the ever-shrinking criteria of the International Technology Roadmap for Semiconductors (ITRS). As interconnect feature sizes are reduced, process-induced residual stress can cause failure of tracks by stress migration. Therefore, the ability to measure the stress and its dependence on process conditions is vital in the fabrication of state-of-the-art integrated circuits.

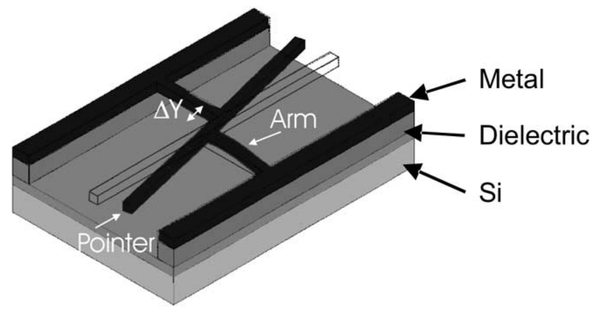

Fig. 1. Three-dimensional (3-D) isometric view of the sensor structure.

With the reduction in physical dimension of state-of-the-art integrated circuits, performance limitations arise from the materials used in the fabrication of the interconnect features. The RC delay of the interconnect (which is the product of the resistance of the conductor with the capacitance due to its surroundings), is now more significant than the delay of the transistor itself. In order to minimize this delay, the introduction of copper in combination with low κ technology has become necessary. In contrast to the traditional SiO_2 dielectric, a number of these low κ materials are polymeric in composition and so the mechanical properties are different, with, for instance, low-yield stress and high thermal-expansion coefficient compared to the traditional SiO_2-based dielectrics.

We have previously demonstrated a rotating-beam-stress sensor, which is suitable for fabrication alongside interconnect features for the direct measurement of process-induced residual stress [1]. The sensitivity of the sensor is sufficient to observe the dependence of residual stress on the deposition conditions used during the sputter deposition of the layer [2]. The sensor structure is shown schematically in Fig. 1. It can be observed that when the fixed beams (labeled as arms) with a separation of ΔY are freed from the underlying dielectric layer (shown in Fig. 1), they contract or expand in order to relieve any residual tensile or compressive stress. As these two arms are offset on opposing sides of the rotating beam (pointer), any deviation in the length of the arms exerts a torque about the center of the sensor structure, causing the pointer arm to rotate.

Finite-element software (ANSYS) has been used to model this rotation as a function of the process conditions and material

Manuscript received June 14, 2005. This work was supported by the Engineering and Physical Science Research Council, U.K., under Grant GR/N32945/01. This work was supported by the Portugese Government through the "Fundação para a Ciência e a Tecnologia" scheme. The X-ray measurements were performed in the frame of the POCTI/33681/CTM 2000 Project, which was approved by the National Foundation for Science and Technology (FCT, Portugal) and the Programa Operacional "Ciência, Tecnologia, Inovação" (POCTI) program, and sponsored by the European Found Fondo Europeo de Desarrollo Regional (FEDER).

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Digital Object Identifier 10.1109/TDMR.2005.857218

TABLE I
PARAMETER SETTINGS USED WITH THE DIFFRACTOMETER COLLECTING DATA FOR THE STRESS-ANALYSIS WAFERS

Planes	Bragg Angle [°]	Angular Step Width [°]	Counting Time per Step [s]	Number of Ψ angles (±60°)	Incident Angles [°]
{422}	137.5	0.05	8	17	5 10
{333}	162.5	0.05	8	17	5 10

properties of the (in this case) aluminum layer [3]. As the plasticity and creep properties of thin films are known to differ from those observed for bulk materials, input parameters for the modeling have been determined by nanoindentation testing in conjunction with finite-element modeling [4].

Previous work has shown the suitability of the sensor structure for the measurement of compressive and tensile stress in aluminum films [5]. This has been achieved by the observation of pointer rotation in both clockwise and anticlockwise directions, depending on the thermal history of the layer.

In this paper, we report the calibration of the sensor for both plasma-enhanced chemical-vapor deposition (PECVD) SiO_2 and polyimide, by comparing the angle of rotation with the in-plane stress extracted from high-resolution X-ray-diffraction measurements.

II. EXPERIMENTAL

A four-circle diffractometer with a high-purity germanium detector has been used to measure the diffraction pattern. The divergence of the incident beam is limited by a pinhole collimator 1 mm in diameter with 0.4° Soller slits. The choice of a punctual spot instead of a linear beam is justified by the use of the Ψ-(or side inclined) geometry, which has a lower absorption than the traditional Ω-method of stress analysis [6].

$K\alpha-Cu$ radiation was selected, because it allows the study of two Al crystallographic planes in the current equipment: {422} at 137.5° and {333} at 162.5°. Stresses have been calculated for both orientations and then averaged to give the final value. If a thin layer is irradiated, the low absorption of the $K\alpha-Cu$ radiation by aluminum represents a constant depth penetrated by the X-rays. As a consequence, the possible stress gradients cannot influence the results, and the calculated stresses will be of the same order of magnitude, even though the data are collected at different incident angles. These angles were defined in studies of the diffracted intensity variation, which showed the highest values for a band between 5° and 10°. Therefore, these two incidence angles were selected for the two families of planes, representing a set of four measurements for each sample. The parameters of the data collection are summarized in Table I.

The texture analysis on the aluminum films has shown a (111) fiber texture, with the fiber axis normal to the surface. However, using low-angle incidence geometry, no effects on the residual-stress analysis were detected; neither scatter of the diffracted intensity, as exemplified in Fig. 2, nor oscillations on the d versus $\sin^2 \Psi$ distributions have been observed. As a result of these findings and the characteristics of the equibiaxial stress state, the stress was determined using the method in [7]. X-ray elastic constants (XEC) of mechanically isotropic material were used, taking into account the weak elastic anisotropy of aluminum.

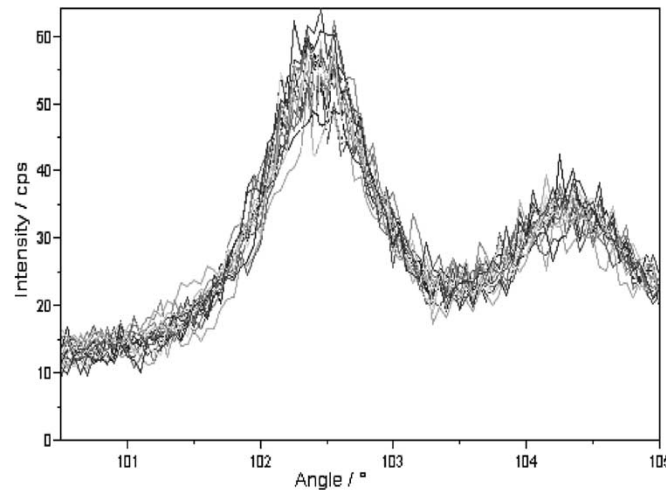

Fig. 2. Representative diffraction peaks of the analyzed samples.

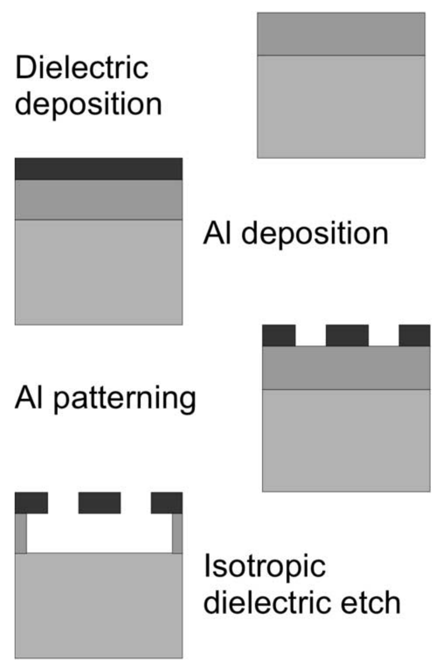

Fig. 3. Cross-sectional process flow.

III. SENSOR FABRICATION

The rotating beam sensors were fabricated on n-type silicon using the process shown schematically in Fig. 3. The intermetal dielectric was deposited on the front face of the wafer. For the control devices, 2 μm of PECVD SiO_2 was deposited at 300 °C, while for the "low κ" devices, a 2-μm layer of P2555 polyimide was spin deposited at 3500 r/min and baked at 310 °C for 20 min in air. Prior to aluminum deposition, the polyimide wafers were subjected to a further 10-min bake in dry N_2 at 435 °C. A micrometer of aluminum was then sputtered at a

TABLE II
RESIDUAL STRESSES CALCULATED BY X-RAY DIFFRACTION

Dielec-tric	Sinter Temp-erature (°C)	In Plane Stress [MPa] {422} Planes α=5°	{422} Planes α=10°	{333} Planes α=5°	{333} Planes α=10°	Average
SiO_2	Not Sintered	54 ± 4	60 ± 6	59 ± 6	69 ± 4	61 ± 5
SiO_2	385	68 ± 9	67 ± 8	65 ± 7	59 ± 7	65 ± 8
SiO_2	400	70 ± 3	69 ± 6	77 ± 8	75 ± 8	73 ± 6
SiO_2	420	83 ± 8	73 ± 4	76 ± 9	58 ± 7	73 ± 7
SiO_2	435	68 ± 8	72 ± 7	67 ± 8	73 ± 5	70 ± 7
P2555	Not Sintered	38 ± 3	42 ± 4	44 ± 7	39 ± 5	41 ± 5
P2555	435	36 ± 5	31 ± 4	26 ± 6	32 ± 4	31 ± 5

target power of 2 kW and ambient pressure of 2 mTorr, before patterning using a 5× stepper and subsequent chlorine-based reactive-ion-etching (RIE) step.

Five chips fabricated using the SiO_2 dielectric were selected from a single diced wafer before being subjected to the range of sintering conditions summarized in Table II. The sinter process consists of ramping the wafers to temperature, then a 25-min soak in 40/60 H_2/N_2 forming gas, followed by air cooling. The isotropic undercut of the aluminum features is performed using hydrogen-fluoride (HF) vapor, before rinsing in deionized (DI) water. Further details of this process can be found in [8].

Sensors released in this manner are affixed to the substrate by stiction, but we have found that because the rotation occurs while the device is in the vapor-etch stage of the process, any stiction which occurs during the rinse does not affect the trends in observed angles of rotation [9].

Two chips employing a polyimide dielectric were also selected. One of these chips underwent the same sinter process as the SiO_2 devices, with a hold temperature of 435 °C, before isotropic removal of the dielectric on both chips was achieved using an atmospheric-pressure oxygen plasma.

After processing, the rotation of the devices is measured using a reflected-light microscope at room temperature with a digitizing frame grabber. The angle of rotation is extracted using custom-written automated image-processing software, with a basic accuracy of 0.1°.

IV. Results and Discussion

The experimental method allowed the determination of four values of the residual stresses for each sample, which are shown in Table II. The errors were calculated from a representative set of measurements. Further analysis of their values suggest that the results are subject to an error of the order of 10% of the stress magnitude. A penetration depth of 0.5 μm was calculated for the wavelength of the X-rays used in this study.

These results show that the as-deposited films, on both SiO_2 and polyimide dielectrics, show a tensile behavior, which is dominated by the mismatch in thermal-expansion coefficient

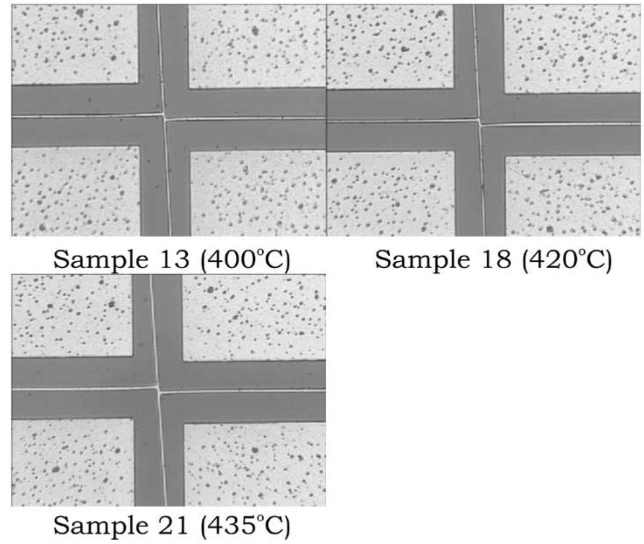

Fig. 4. Reflected light micrographs for sensor structures with 1-μm feature width fabricated on SiO_2 intermetal dielectric after different sinter hold temperatures.

between the aluminum and the silicon substrate. The wafers were not cooled during the sputter process and the incident flux of energetic atoms at the surface of the wafer raises their temperature. Once this rises above 150 °C, creep mechanisms can relax any intrinsic stress from the growth process. Upon cooling, this low-stressed aluminum layer is forced into tension by the extrinsic (thermal) stress.

The tensile thermal stress is greater than the compressive intrinsic stress in the film that originates from atomic peening [10]. Defects and interstitial atoms are created in the layer due to momentum transfer from the energetic incident atoms, and this leads to the generation of a compressive stress.

During the high-temperature soak in the sinter process, creep mechanisms relax the stress in the layer. The measured stress in the layer $\sigma_{\rm measured}$ can be expressed as the sum of the three components

$$\sigma_{\rm measured} = \sigma_{\rm intrinsic} + \sigma_{\rm thermal} - \Delta\sigma_{\rm relaxation} \quad (1)$$

where $\sigma_{\rm intrinsic}$ and $\sigma_{\rm thermal}$ are the intrinsic and thermal stress in the aluminum, respectively, and $\Delta\sigma_{\rm relaxation}$ is the stress relaxation that takes place during deposition.

At the higher sinter temperatures, there is a complete relaxation of the stress within the 25-min soak time, which can be seen as a saturation of the stress values at around 73 MPa. Sintering at 385 °C for 25 min does not fully relax the compressive stress in the layer, and this is reflected in the reduced value of stress extracted from the X-ray-diffraction measurements.

Fig. 4 shows reflected-light micrographs of a sensor with an arm separation of 4 μm, arm length of 140 μm and a feature width of 1 μm for chips 13, 18, and 21. Previous work has shown that a larger angle of rotation is observed for features with a 1-μm width, which comprise a complex hinge feature [10]. Chip 13 was sintered at 400 °C, chip 18 at 420 °C and chip 21 at 435 °C.

It can be seen from Fig. 4 that the sensor rotation is similar for the three samples. The rotation angles extracted from the

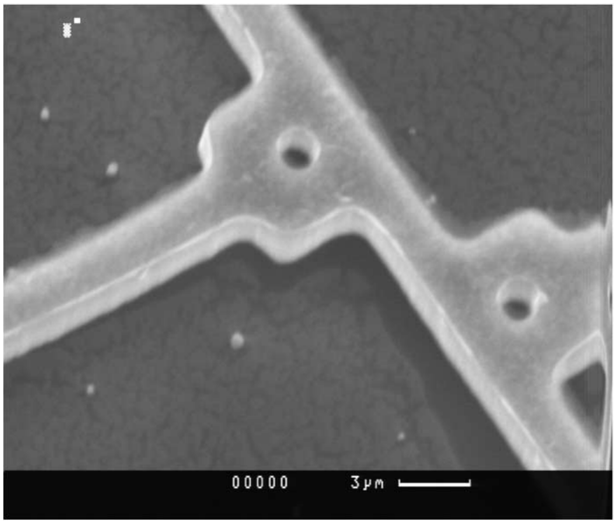

Fig. 5. Scanning electron micrograph of the hinge region of a sensor designed for reducing plastic deformation [11], showing feature rounding from the photolithographic process.

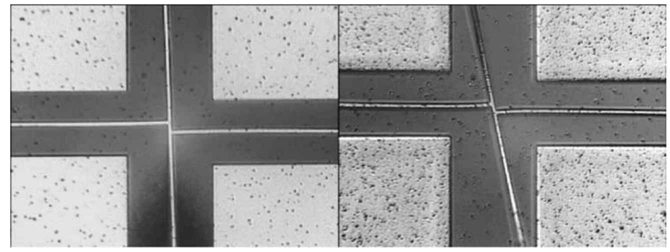

Fig. 6. Reflected light micrographs for sensor structures with 1-μm feature width. (left) SiO_2 dielectric, (right) polyimide dielectric.

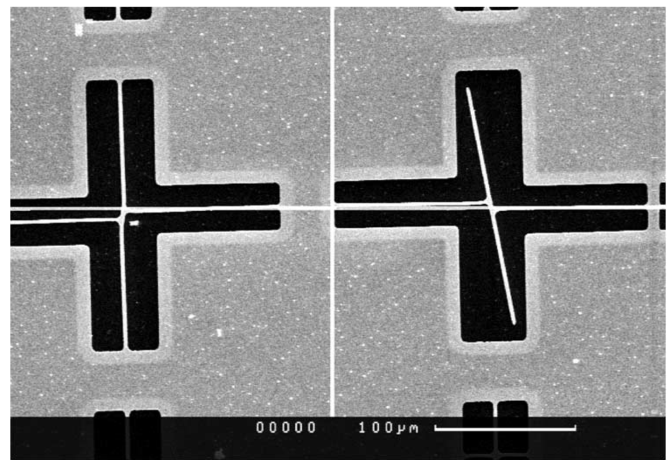

Fig. 7. Scanning electron micrograph of two adjacent sensors on a polyimide dielectric, showing the origin of the enhanced rotation.

image-processing software give an angle of rotation of 2.6° with a standard deviation of 0.61°. This large standard deviation in the observed angle maybe due to the nonuniformity effects that result from the photolithographic process used in the fabrication of these sensors, specifically corner rounding, where the expansion arms attach to the pointer, as shown in Fig. 5. Previous work [1] has shown that the reproducibility of the physical dimension of the hinge area can have a pivotal role in the observed angle of rotation. The angle of rotation observed for sensors with a nonideal hinge geometry is lower than would be expected and so the angles given previously should be interpreted as a lower limit.

Equating the angle of rotation to the extracted in-plane stress, we can observe that each degree of rotation for the sensor arm indicates a stress of 28 MPa. ANSYS predictions for the same sensor geometry give a stress of 14 MPa per degree of rotation for this sensor design. The difference between these figures is due to variations that arise from the pattern-transfer process and the compressive nature of any residual SiO_2 from the isotropic-release etch [8]. Optimization of the photolithographic process for patterning of the sensor features will increase the observed rotation, which enables the resolution of lower stress levels for an equal rotation. As has previously been mentioned, the image-processing system developed in this study measures the angle of rotation with an accuracy of 0.1°, which equates to a stress of 2.8 MPa.

Fig. 6 shows the angle of rotation for two identical sensors fabricated on: 1) SiO_2; and 2) polyimide interlayer dielectrics. This shows that the angle of rotation for the polyimide sensor (10.2°) is far greater than that observed for the equivalent sensor fabricated using SiO_2 (2.6°). These angles of rotation would indicate a stress of 286 and 73 MPa, respectively, using the calibration constant given previously. The measured stress of the SiO_2 device is in close agreement with previous sensors fabricated using this interlayer dielectric. However, the stress calculated from the rotation of the polyimide device is far higher than values extracted from the X-ray measurements given in Table II.

Fig. 7 shows the origin of this enhanced rotation for the polyimide samples. The sensor to the left of the micrograph is designed for release by focused ion beam (FIB) or laser ablation after the isotropic removal of the underlying dielectric and so the ends of the pointer meet the surrounding metallization. The cross hair on the figure shows that the expansion arms for the sensors lie in a straight line, indicating that the observed enhanced rotation is not due to any deformation perpendicular to the expansion arms. The tensile stress in the arms can be observed from the rotation of the central portion of the pointer between the arms. Although the angle of this rotation is large, the lateral displacement is small. At the right end of the arm, the figure clearly shows evidence of undercutting of the surrounding metal (lightening of the color) and only a relatively thin region separates the two sensors.

The compliant nature of the dielectric allows a significant load transfer through this anchor region between the sensors, especially when the lateral extent has been reduced from the undercut during processing. Using finite-element simulations, we have investigated the effect of this load transfer through the region by varying the fixed points on the sensor structure shown in the upper portion of Fig. 8. The results for simulation A have the points marked A in the figure fixed rigidly to the substrate, similar to that of simulations B and C. The figure shows that constraining the center of the adjacent sensor structures gives a predicted angle of rotation that accurately describes the experimental data. Hence, the load transfer through the anchor

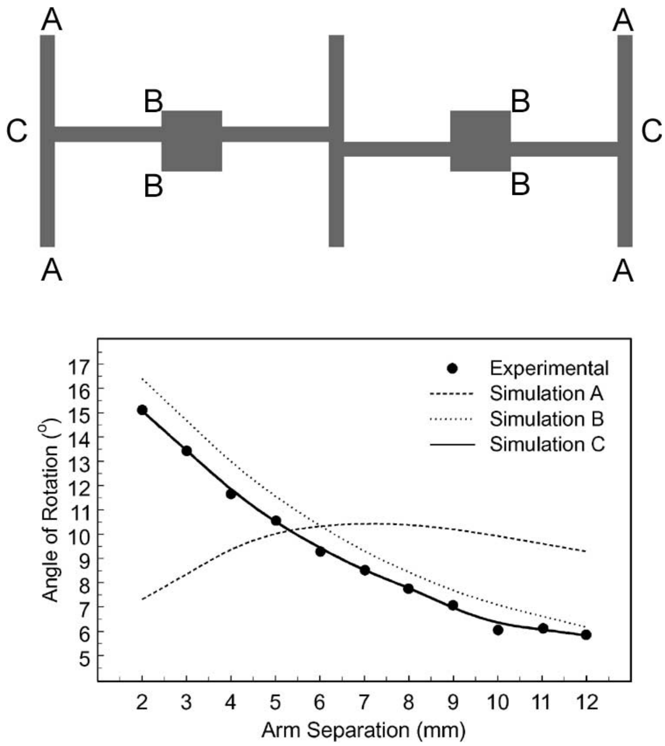

Fig. 8. Influence of the anchor points on the angle of rotation and experimental data for a sensor of identical dimensions.

point at the end of the arms of the sensor gives an effective arm length that is double that defined in the patterning of the structure, giving the enhanced rotation of the pointer.

Hence, the sensor structure is ideally suited to the measurement of stress in devices with polymeric low-κ intermetal dielectrics, but the compliant nature of the dielectric places restrictions on the size of the anchor regions at the ends of the expansion arms.

V. CONCLUSION

We have demonstrated that the rotating-beam-stress sensor can be used to observe the variation of stress with sinter conditions in aluminum interconnect features. Extrinsic stress from the thermal-expansion mismatch is shown to dominate the measurements at room temperature due to the reduction of intrinsic stresses by creep mechanisms at temperatures above 150 °C. By comparing the angle of rotation of our stress-sensor structure (with values extracted from high-resolution X-ray-diffraction measurements), we have shown that the sensitivity of the technique is better than 2.8 MPa and that the overall accuracy is limited by the photolithographic process used during fabrication. The use of techniques such as optical proximity correction (OPC) in future mask designs could alleviate these limitations [12].

We have used the sensor structure to observe the effect of a compliant intermetal dielectric on the stress in the aluminum film and found that this stress is reduced by a factor of two. The enhanced rotation observed in the released sensors on the polyimide is linked to the load transfer through the anchor point, which is enhanced by the undercut during the isotropic etch. This leads to the conclusion that although this technique is suitable for the observation of stress in low-κ dielectric systems, different design rules are required from those used for conventional inorganic layers.

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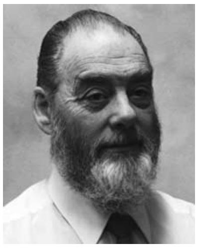
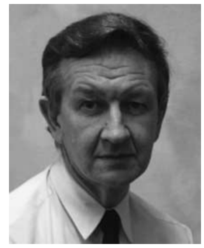


Alan M. Gundlach received the B.Sc. degree in physics in 1959 and the M.Sc. degree in 1965, from the University of London, U.K.

He was employed in the semiconductor industry for 19 years, since 1959, initially with A.E.I. Radio and Electronics Components Division and with Texas Instruments, Ltd., working on the manufacture of bipolar discrete devices and integrated circuits, and later with Elliott Automation Microelectronics, Ltd., and with General Instrument Microelectronics, Ltd., as MOS Process Development Manager. In 1978, he was appointed to a Senior Research Fellowship at the University of Edinburgh, Edinburgh, U.K., in the role of Operations Manager of the Edinburgh Microfabrication Facility, in which capacity he has been responsible for designing and installing processes ranging from silicon machining to complete CMOS fabrication sequences. He is currently engaged in research in the area of interfacing biological materials with silicon-based microstructures.



J. Tom M. Stevenson received the B.Sc. degree in physics in 1967, the M.Sc. degree in instrument design in 1969 from the University of Aberdeen, Aberdeen, U.K., and the Ph.D. degree from the University of Edinburgh, Edinburgh, U.K., in 1988.

He spent five years at Ferranti, Ltd., Dalkeith, as a Development Engineer on moire measuring systems. In 1974, he joined Wolfson Microelectronics Institute to work on the design of a pattern generator for the production of integrated circuits. In 2003, he was appointed Operation Director at the Scottish Microelectronics Centre, University of Edinburgh, U.K. His main research interests are in optical lithography, optical-measurement techniques, and chemical mechanical polishing (CMP).