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A novel surface micromachining process to fabricate AlN unimorph suspensions and its application for RF resonators

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Abstract

A novel surface micromachining process is reported for aluminum nitride (AlN) thin films to fabricate piezoelectric unimorph suspension devices for micro actuator applications. Wet anisotropic etching of AlN thin film is used with a Cr metal mask layer in the microfabrication process. Tetra methyl ammonium hydroxide (TMAH) of 25 wt.% solution is used as an etching solution for the AlN thin films. Polysilicon is used as a structural layer. Highly *c*-axis oriented AlN thin films are deposited by RF reactive sputtering. Thin layers of chromium on either side of the AlN are used as top and bottom electrodes and also as a mask to etch the AlN and polysilicon layers. The fabricated suspended unimorph structures are tested for scattering parameters using a vector network analyzer. Results show resonant frequencies of devices above 1.7 GHz with an effective electromechanical coupling factor, $K^2_{\mathrm{eff}} \approx 1.7\%$.

Keywords: Aluminum nitride (AlN); Wet anisotropic etching; Piezoelectric unimorph suspension; Thin film bulk acoustic resonator (TFBAR)

1. Introduction

Aluminum nitride (AlN) thin films are interesting in MEMS applications because of their piezoelectricity, high acoustic velocity and chemical stability at high temperatures. Surface micromachined AlN thin film piezoelectric microstructures find many applications in modern telecommunication devices in the form of resonators and filters. A sandwich of AlN thin film between two electrode layers forms a basic configuration of piezoelectric unimorph structures as shown in Fig. 1. Applying a cyclic electric field across this piezoelectric AlN capacitor results in the AlN thin film to expand and contract alternatively causing excitation of acoustic waves. It is also known that thin structural layers can be beneficial for certain applications such as thin film bulk acoustic resonators (TFBAR). The quality of AlN thin films is decisive for electromechanical coupling. AlN grown with (0 0 2) orientation perpendicular to the substrate is favourable for such piezoelectric device applications [1]. Methods such as MOCVD, MOVPE, PLD, RF sputtering, sublimation etc. are used in the literature [2–4] to grow AlN thin films on several substrates. RF reactive sputtering is one of the common methods used to deposit polycrystalline AlN thin films with preferentially (0 0 2) orientation perpendicular to the substrate in many kinds of substrates [5].

AlN thin film patterning, etch selectivity to the mask layer, compatibility with surface micromachining processes and minimum feature size of free-standing piezoelectric microstructure are key factors in the fabrication process. Wet patterning of AlN thin film using 0.6 wt.% tetra methyl ammonium hydroxide (TMAH) solution at room temperature and a Cr mask layer was already reported [6]. Fabrication of SOI-based AlN thin film suspended devices involving a very thick (15 μm) silicon structural layer was reported earlier [7]. Also, micromachined AlN piezoelectric resonating structures on SiO_2 structural layers with germanium as a sacrificial layer have been reported recently [8].

This paper reports on a new silicon-based surface micromachining process for integrating AlN thin films into a surface micromachining process and the fabrication of AlN unimorph suspension devices. These devices use SiO_2 as a sacrificial layer. Anisotropic wet etching of AlN using TMAH (25%) solution is used to pattern AlN microstructures using a Cr layer that simultaneously serves as top electrode. The dimensions of the active

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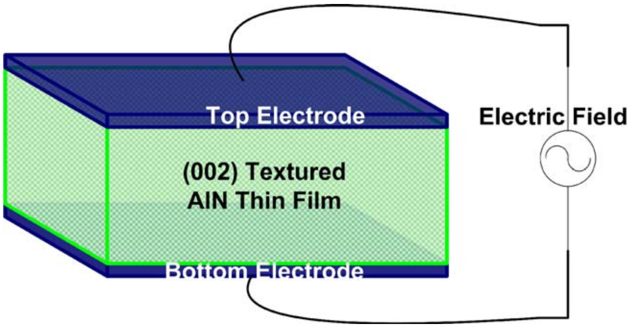

Fig. 1. A simple piezoelectric resonating beam with a sandwich of AlN between electrodes on polysilicon structural layer.

part of the device are (480 μm × 25 μm). The characteristics of these devices are measured using HP 8510C vector network analyzer (VNA) and an RF probe station.

2. Deposition of AlN thin films

Highly (0 0 2) textured AlN thin films are necessary for piezoelectric device applications. A Nordiko-2000 RF reactive sputtering machine has been used for the deposition process. The used deposition parameters for AlN thin films are shown in Table 1. For piezoelectric actuating structures, a stack of Cr/AlN/Cr layers was deposited in a single run without breaking the vacuum to ensure better adhesion of the Cr layers with AlN. The deposition was done at substrate temperatures <400 °C which is compatible with CMOS processes.

Fig. 2 shows X-ray diffraction ($\theta - 2\theta$) of a (0 0 2) oriented AlN thin film deposited on a Cr metal layer electrode. It indicates a high intensity (0 0 2) diffraction peak of AlN at 35.93° and its full width half maximum (FWHM) value was <3° as measured from rocking curve measurements. A narrow, sharp (0 0 2) diffraction peak indicates highly textured AlN grains with *c*-axis perpendicular to the substrate enabling good piezoelectric properties [1]. Fig. 3 shows an SEM image of dense columnar AlN thin film without trapped voids. The estimated grain size from XRD measurement by Scherrer's formula [9] is approximately 20–30 nm.

3. Anisotropic wet etching of AlN

AlN thin films on silicon substrates were used to study the etching behaviour of AlN thin films with Cr mask layers. The thickness of the mask layer is about 40–50 nm and it was found to be dense and uniform over the AlN thin films. The Cr layer was patterned first to make etch openings for AlN. It was done by a UV photolithography process with a mask having regular beam structures with a minimum width of 2 μm. A TMAH (25 wt.%) solution was used to etch AlN at room temperature without stirring the solution by external means. The etch depth was measured using a Dektak surface profiler and the etch rate was determined as 22 nm/min. The samples were investigated by scanning electron microscope (SEM) to study the etch profile under the Cr mask layer. A high etch selectivity of AlN with the Cr metal mask layer was found and it is shown in Fig. 4. The anisotropic etch profile of AlN under the Cr mask shows that the columnar layer of AlN thin films has been etched selectively with negligible lateral etching under the Cr mask layer (<2 nm/min).

Table 1
AlN deposition parameters

Parameters	Values
Base pressure (mbar)	$<3 \times 10^{-7}$
Substrate layer	Cr/polysi/SiO_2/Si
Sputter pressure (mbar)	3.3×10^{-3}
RF power (W)	350
Ar:N_2 flow rate (sccm)	8:3
Substrate temperature (°C)	360
Target-substrate distance (cm)	6

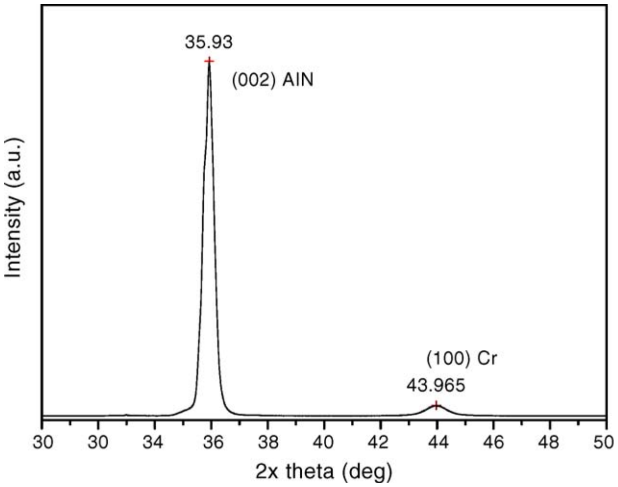

Fig. 2. X-ray diffractogram of (0 0 2) oriented AlN thin film on a Cr electrode layer.

4. Surface micromachining process

A schematic process description to fabricate AlN piezoelectric free standing microstructures is shown in Fig. 5. A stack of Cr/AlN/Cr layers forms an active area for piezoelectric actua-

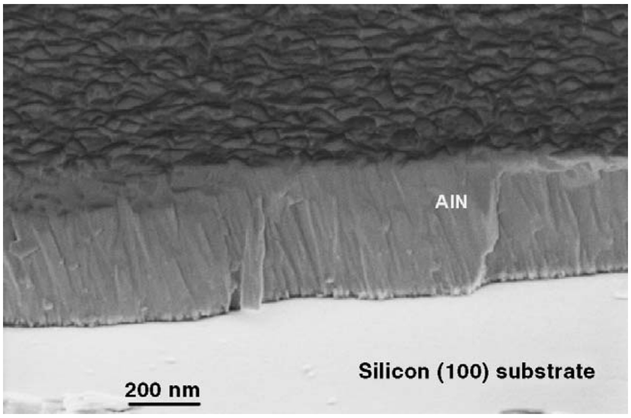

Fig. 3. RF reactive sputtered densely packed AlN thin film with (0 0 2) texture without voids.

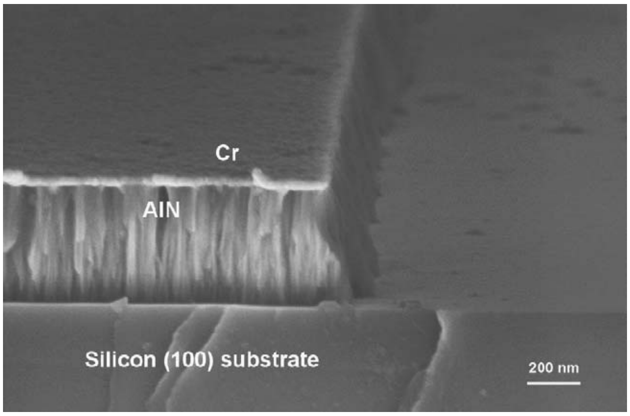

Fig. 4. Anisotropically etched patterns of AlN thin film under Cr mask layer using TMAH (25 wt.%) solution.

tion on the polysilicon structural layer. Three masks were used in the fabrication process. The first mask was used to define the area to be freed by sacrificial etching and the second and third masks were used to pattern the electrode area for top and bottom electrode, respectively.

An ordinary p-type (1 0 0) silicon wafer with 100 nm thick low pressure chemical vapour deposition (LPCVD) silicon-rich-nitride (low stress SiRN) isolation layer forms a basic substrate. SiO_2 (1.2 μm) and polysilicon (1 μm) layers deposited by LPCVD processes were used as sacrificial and structural layers, respectively. The stress in the polysilicon was reduced by annealing at 1050 °C. The stack of Cr/AlN/Cr layers was sputter deposited in a single run without breaking vacuum from the main chamber. This provides better adhesion of the Cr film on the AlN during sacrificial release etching. The AlN thin film of more than 1 μm thickness was deposited between sandwiches of 60 nm thick Cr layers. The top Cr layer serves effectively three purposes: (1) as one of electrodes to actuate the piezoelectric unimorph structure, (2) as a mask to pattern the AlN thin film and (3) as a mask to etch the polysilicon by the Bosch DRIE process.

A SEM image of a piezoelectric microstructure before it is released by the sacrificial etching is shown in Fig. 6. It shows an anisotropic etched surface of the AlN thin film using TMAH 25% solution at room temperature. The free-standing piezoelectric suspension microstructure is shown in Fig. 7. It consists of four unimorph AlN unimorph structures sharing a common bottom electrode, connected with a square shuttle beam.

Each arm of the suspension beam has an active area of actuation (480 μm × 25 μm). The freed-four active arms on the polysilicon structural layer form a complete piezoelectric suspension and are connected to a square shuttle beam. Electrical

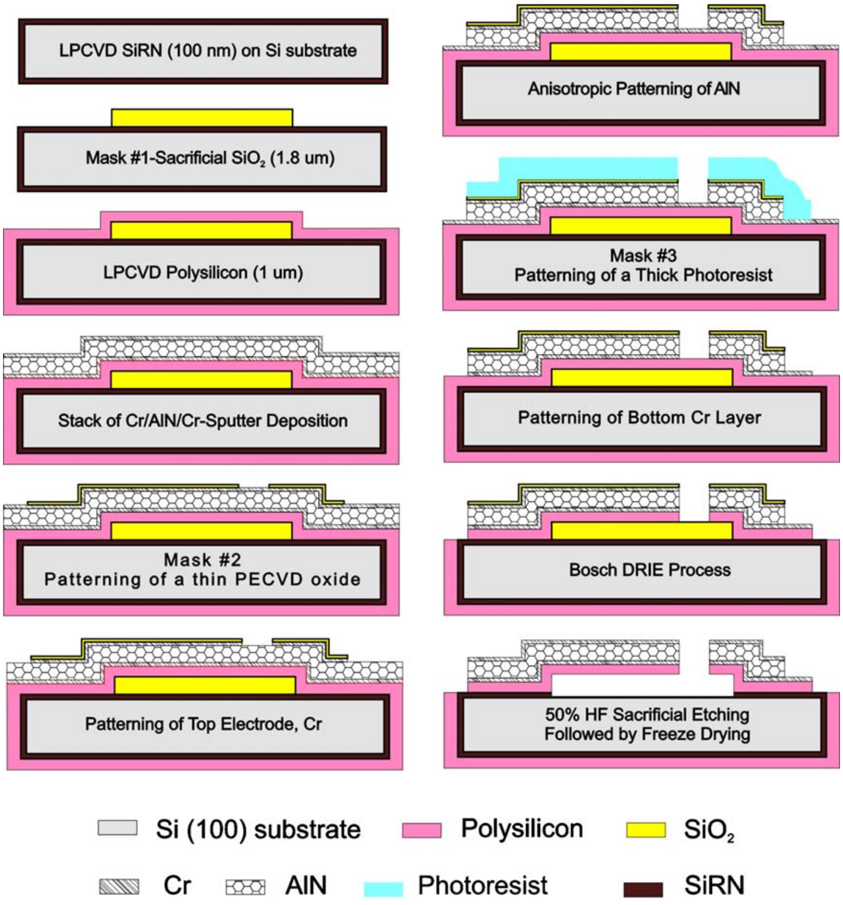

Fig. 5. Schematic fabrication process steps for piezoelectric AlN unimorph microstructures.

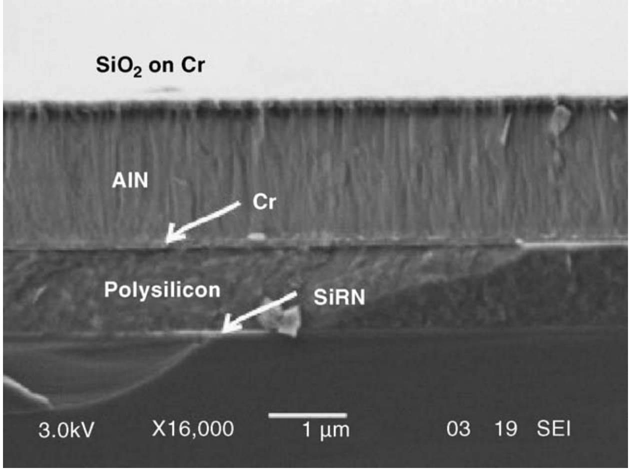

Fig. 6. A cross sectional image of piezoelectric Cr/AlN/Cr stack on polysilicon layer before sacrificial layer release.

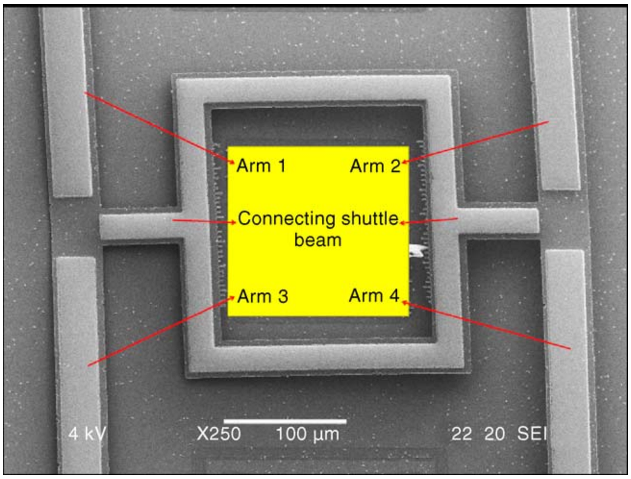

Fig. 7. Freed suspended arms with four unimorph structures connected by a square shuttle beam.

excitation can be done individually on each arm of the suspension device.

5. Results

The fabricated structures were characterized using a vector network analyzer (VNA) for a frequency range of 1–2 GHz in a one-port resonator configuration. An RF probe station along with a HP 8510C VNA was calibrated using a standard calibration sample for a characteristic impedance of 50 Ω in open, short and load modes. Ground–signal–ground (G–S–G) probes were used with a spacing of 125 µm between them. The calibration procedure was repeated for every selected frequency range of measurements. Probing has been made at one of the arms of the suspension device. Fig. 8 shows the wide band response of the reflection coefficient (S_{11}) measured in one-port resonator configuration for a span of frequencies from 1 to 2 GHz on one of the arms of the suspension device with an active area (480 µm × 25 µm). A narrow band response with S_{11} measured at a low point of −7.6 dB is shown in Fig. 9. The measured impedance of the resonating arm is shown in Fig. 8 for a narrow band of 1.6–1.9 GHz.

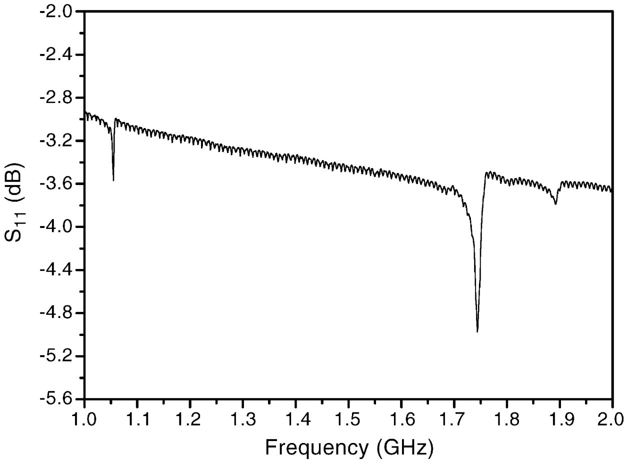

Fig. 8. Measured wide band response of the reflection coefficient, (S_{11}) on one of the arms of the suspension.

The effective electromechanical coupling is related to the difference in series and parallel resonant frequencies [10–11]. The percentage of effective electromechanical coupling constant, (K^2_{eff}) and the quality factor ($Q_{\mathrm{s/p}}$) can be calculated using the following equations:

$$k^2_{\mathrm{eff}}\,(\%) = \frac{\pi^2}{4}\left[\frac{f_\mathrm{p}-f_\mathrm{s}}{f_\mathrm{p}}\right] \times 100$$

$$Q_{\mathrm{s/p}} = \frac{f_x}{2}\frac{\mathrm{d}\angle Z_{\mathrm{in}}}{\mathrm{d}f}\bigg|_{f_x=f_{\mathrm{s/p}}}$$

The series and parallel resonant frequencies were found to be 1.7725 and 1.78488 GHz, respectively. Based on the above equations, the effective electromechanical coupling factor was found as 1.7% and the measured bandwidth was 12 MHz. From the frequency response of the impedance curve, the calculated quality factor was 41. The results are comparable with the SOI-based suspension type resonators with 2 µm thick AlN thin film [7]

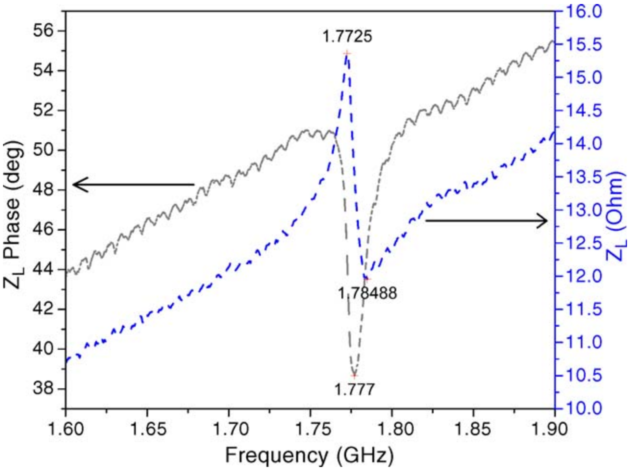

Fig. 9. A narrow band impedance response of a single arm of the suspended device.

and showed a bandwidth of 16 MHz with an effective electromechanical coupling factor of 2.4%.

6. Conclusions

AlN thin film piezoelectric microstructures on polysilicon structural layers were fabricated by a surface micromachining process for actuator applications. Highly textured AlN thin films were sputtered on Cr metal layers by RF reactive sputtering in a single run process to form unimorph piezoelectric structures. Top Cr layers are used as electrode and mask to etch the AlN thin films and polysilicon layers. Anisotropic wet etching of AlN thin film is unique in this process with negligible lateral under-etching below the mask layer. One-port RF characterization on a four arm suspension device with an active part of (480 μm × 25 μm) demonstrates its application as thin film resonators above 1.7 GHz. Effective electromechanical coupling constant, $K^2_{\text{eff}} \approx 1.7\%$ and the quality factor, $Q_{\text{s/p}} \approx 41$ were obtained.

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Biographies

S. Saravanan received his MS by research degree in precision engineering and instrumentation from the Indian Institute of Technology, Madras, India, in 2000. Since 2001, he has been doing his PhD in the MESA+Institute for Nanotechnology, University of Twente, The Netherlands. His research interests are microactuators and microfabrication processes. His thesis work involves the integration of AlN thin films in surface micromachining process technology and realization of its microstructures as piezoelectric actuators and thin film acoustic resonators.

J.W. Erwin Berenschot received the BSc degree in applied physics from the Technische Hogeschool in Enschede, The Netherlands, in 1990. Since 1992, he has been employed as a micromachining engineer at the transducer science and technology group of the MESA+Research Institute. His main research area is development and characterization of etching and deposition techniques for the fabrication of micro systems. He has published over 30 reviewed journal papers on micromachining and related topics, and four patent applications.

Dr. Gijs Krijnen received his MSc degree in electrical engineering with honours from the University of Twente following a study on magnetic recording carried out at the Philips Research Laboratories, Eindhoven. In 1992, he received the doctorate degree with honours from the same university and was rewarded the 1993 Veder price of the Dutch Electronics and Radio Engineering Society (NERG) for his PhD thesis on nonlinear integrated optics devices. From 1992 to 1995, he was a fellow of the Royal Netherlands Academy of Arts and Sciences and studied second- and third-order nonlinear integrated optics devices. In this period, he was a visiting scientist at the Center for Research and Education in optics and lasers in Orlando, Florida, USA. In 1995–1997, he worked on integrated optic devices for optical telecommunication simultaneously at the University of Twente and the Delft University of Technology. Since1998, he is associate professor in the transducers science and technology (TST) group of the MESA+Research Institute and responsible for the micro-actuator research. His current interests include micro-electro-mechanical systems (MEMS) including bio-mimetic flow-sensors and micro-actuators and nano opto-electro mechanical systems (NOEMS).

Miko Elwenspoek (born 9 December 1948 in Eutin, Germany) studied physics at the Free University of Berlin (West). His masterthesis dealt with Raleigh scattering from liquid glycerol using light coming from a Mössbauer source. From 1977–1979, he worked with Prof. Helfrich on lipid double layers. He conducted experiments on osmotic shrinkage of giant lipid vesicles, and wile preparing light scattering experiments from those giant vesicles worked out the theory of light scattering from large aspheric particles and spherical bubbles. In 1979, he started his PhD work with Prof. Quitmann. This work dealt with relaxation measurements on liquid metals and alloys, in particular alkali metal alloys. The experimental technique used in these experiments is related to nuclear magnetic resonance, but the alignment of the nuclei is done by a nuclear reaction using high energetic α-radiation. This work resulted in a thesis (Freie Universität Berlin, 1983). In 1983, he moved to Nijmegen, The Netherlands, to study crystal growth in the group of Prof. Bennema of the University of Nijmegen. The emphasis lay on growth of organic crystals (in particular naphthalene) from melt and solution. In 1987, he went to the University of Twente, to take charge of the micromechanics group that was part of the sensors and actuators lab, now MESA+Research Institute. Since then his research focused on microelectromechanical systems. In the first years the work was concentrated to coaching design and modelling of micropumps and resonant sensors by PhD students, but since the beginning of the 90ths more and more attendance was given to electrostatic microactuators, including electrostatic motors, and thermal and electromechanical actuators with the aim of building microrobots. Further, research in fabrication technology got much attention, with emphasis on physical chemistry of wet chemical anisotropic etching, materials science of thin films (such as ZnO, TiNi, PZT and fluorocarbon), reactive ion etching of silicon, polymers and metals, wafer bonding and chemical-mechanical polishing. In 1996, he became full professor in transducers science and technology at the Faculty of Electrical engineering, University of Twente. He is fellow of the Institute of Physics and of IEEE. He is enthusiastic on teaching on academic level. In 2001, students elected him as the the best lecturer in the electrical engineering program. He was a co-founder of the education "advanced technology" at the UT and of the master nanotechnology. He enjoys classical music, painting and drawing, and hiking. He is co-author of two books (Silicon Micromachining, by M. Elwenspoek and Henri Jansen, Cambridge University Press, Cambridge, 1998; Mechanical Microsensors, by M. Elwenspoek and Remco Wiegerink, Springer, Heidelberg, 2001), and (co)author of ca. 300 scientific papers.