Micromechanical Voltage Reference Using the Pull-In of a Beam

Edmond Cretu, *Member, IEEE*, Luis Alexandre Rocha, and Reinoud F. Wolffenbuttel, *Senior Member, IEEE*

***Abstract*—The pull-in voltage of a single-side anchored free-standing beam, under lateral deflection, has been investigated for application as a dc voltage reference. Two sets of electrodes, alongside the tip, are used for parallel-plate type of electrostatic actuation of the 200 μm long beam in the plane of the wafer. Another set of buried electrodes is aligned with the plate electrode at the free-standing tip and is used as a differential capacitor for the simultaneous detection of the displacement, with the purpose to determine the stability border and thus the pull-in voltage. The single-end clamping ensures that the pull-in voltage is insensitive to technology-induced stresses. A two-dimensional (2–D) energy-based analytical model for the static pull-in is compared with measurements. Bifurcation diagrams are computed numerically, based on a local continuation method. Devices have been designed and fabricated in an epi-poly process. Measurements are in agreement with modeling and confirm a pull-in voltage in the 9.1–9.5 V range. Reproducibility is limited by hysteresis and charging of the dielectric layer in between the electrodes. The device can be operated in feedback or as a seesaw, by using the two sets of electrodes.**

***Index Terms*—DC voltage reference, microelectromechanical systems (MEMS), pull-in.**

I. INTRODUCTION

MEMS technology is gradually also penetrating into mainstream instrumentation and measurement (I&M) applications [1]–[8]. A critical component in many professional instruments is the internal dc reference. The pull-in voltage of beams of different designs has been investigated with the purpose of using the micromechanical structure as an on-chip voltage reference [6], [8]. Such a device may find application in integrated circuits, next to the conventionally used bandgap reference, and in metrology, where Zener references are widely used as so-called "transfer standard." The latter application area is especially promising, as the operation of a Zener diode is based on avalanche breakdown and is associated with a high noise level.

The electrostatic force in a vertical field is inversely proportional to the square of the deflection and the restoring spring force of the beam is, in a first approximation, linear with deflection. Therefore, an unstable system results in case of a deflection beyond a critical value. The pull-in voltage $\mathrm{V_{pi}}$ is defined as the voltage that is required to obtain this critical deflection. The basic phenomenon is the loss of stability at the equilibrium position $\overline{x}^*$, where the elastic forces equilibrate the electrostatic ones. Two methodologies are generally used:

1) the dynamic system approach, in which the electromechanical system is described by a set of differential equations, and an analysis of the stability of its equilibrium points is performed (indirect Lyapunov method).
2) the variational approach, in which the equilibrium points and their stability are determined by studying the variations of the total energy $U(\vec{x}, V) = U_{elastic}(\vec{x}) + U_{electric}(\vec{x}, V)$. The equilibrium points $\vec{x}_{eq}$ are given by solving the system of equations $(\partial U/\partial \vec{x})(\vec{x}_{eq}) = 0$; these are stable if $U(\vec{x}_{eq})$ is a local minimum, which is determined by the sign of eigenvalues of $(\partial^2 U/\partial \vec{x}^2)(\vec{x}_{eq})$. The pull-in voltage is the value of the applied voltage for which the physical equilibrium point loses its stability [9]. The potential energy is composed of the elastic mechanical energy $\mathrm{U_{elastic}}$, and the electrostatic energy stored in the electric components $\mathrm{U_{electric}}$. The elastic energy has two components: the built-in strain energy component $\mathrm{U_{build\text{-}in}}$ and the bending energy resulting from external applied forces $\mathrm{U_{bending}}$.

This second approach is used in the next section for the modeling.

So far, the pull-in effect has been mainly investigated for two reasons. The first is to determine the dynamic range limitations of an electrostatic actuator due to pull-in. Basically, pull-in causes the deflection due to electrostatic force to be limited to one-third of the gap between the electrodes, in the case of a motion perpendicular to the capacitor plate orientation [9]. This effect also limits the dynamic range of capacitive accelerometers operating in the feedback mode. The second field of application is in the characterization of the structural material in a surface micromachining process (usually polysilicon) [10]. The residual stress level is an important material property, as it largely determines the load-deflection characteristic in a double-sided clamped structure, in which this stress level cannot be released in an elongation. Generally, a taut beam is desirable, which implies a low tensile stress in the material. Thermal anneal is required to convert the compressive stress in the as-deposited material into such low tensile stress layer [11]. The pull-in voltage of a double-sided clamped structure reduces with compressive stress, due to the dependence on by the strain energy $\mathrm{U_{built\text{-}in}}$. Therefore, measurement of the pull-in voltage at given device dimensions is a good indicator for the residual stress in a beam.

In this paper, the pull-in voltage is exploited for the realization of a dc voltage reference. For long-term stability, the residual

Manuscript received March 1, 2001; revised July 30, 2001.

E. Cretu is with the Delft University of Technology, ITS/Et, DIMES, 2628 CD Delft, The Netherlands and also with Melexis, Tessenderloo, Belgium.

L. A. Rocha and R. F. Wolffenbuttel are with the Delft University of Technology, ITS/Et, DIMES, 2628 CD Delft, The Netherlands.

Publisher Item Identifier S 0018-9456(01)10921-6.

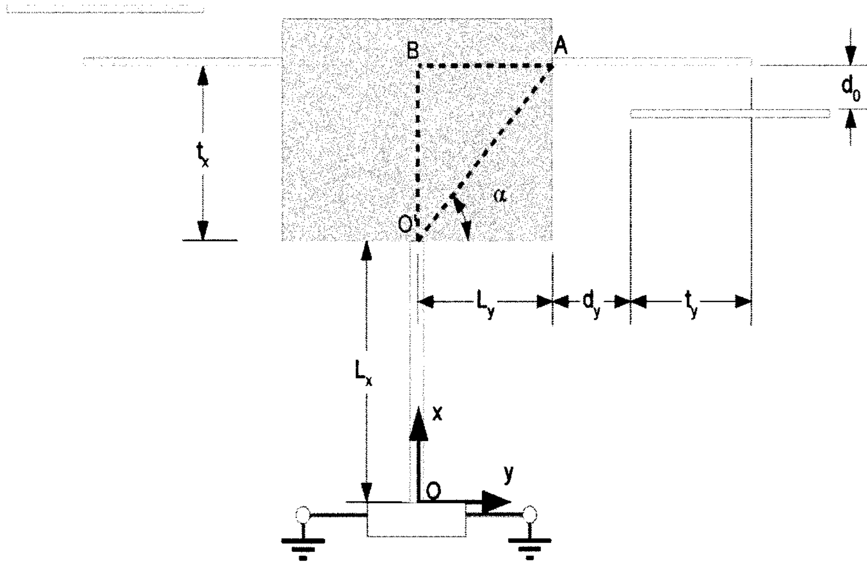

Fig. 1. Single-side clamped structure.

stress should not affect V_{pi}. Therefore, a single-side anchored beam with the other end free-standing should be used or the beam should be suspended using folded tethers at each end [12]. Both approaches ensure $U_{\text{build-in}} = 0$.

II. Modeling the Pull-In Structure

As long-term stability is the most important property of the device, the modeling was based on a single-sided clamped beam fabricated using crystalline material. First, analytical modeling was used and the results were subsequently verified using finite element modeling (FEM). The specifics of the analytical modeling used are as follows.

1) It is applied to an elastic beam, clamped at one end, and actuated by an electrostatic momentum at the free end, as shown in Fig. 1. Thus the built-in strain energy is described by: $U_{built\text{-}in} = 0$. The dimensions are: $L_x = 200\ \mu m$, $L_y = 98\ \mu m$, $d_y = 8\ \mu m$, and $t_y = 50\ \mu m$.
2) The energy balance is evaluated using two parameters (w_1 and φ_1) to fully determine the configuration (Figs. 1 and 2). The elastic energy is described by

$$U_{elastic}(w_1, \varphi_1) = \frac{1}{2} EI_y \int_0^{l_x} \left(\frac{\partial \varphi}{\partial x}\right)^2 dx = \frac{2EI_y}{L_x}\left(\varphi^2 - 3\varphi_1 \frac{w_1}{L_x} + \left(\frac{w_1}{L_x}\right)^2\right).$$

3) The electrostatic energy [taking $(w_1, \varphi_1) = (0, 0)$ as zero-level energy] is described by

$$U_{electric}(w_1, \varphi_1; V) = -\tfrac{1}{2}V^2\left[C(w_1, \varphi_1) + C(-w_1, \varphi_1) - 2C_0\right].$$

The pull-in voltage can be found analytically by solving the determinant equation

$$\left|\frac{\partial^2 U(w_1, \varphi_1; V)}{\partial \vec{x}^2}\right| = 0$$

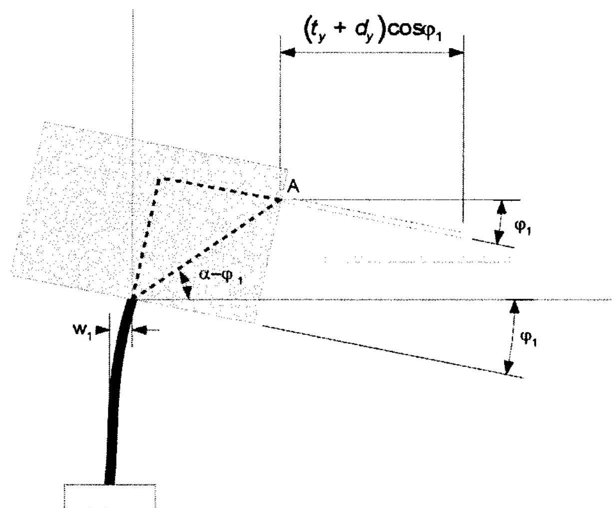

Fig. 2. Identification of the state variables used in the model.

in variable V. Here, $U(w_1, \varphi_1; V) = U_{elastic}(w_1, \varphi_1) + U_{electric}(w_1, \varphi_1; V)$, and the state variables (w_1, φ_1) correspond to the equilibrium position determined from

$$\left|\frac{\partial U}{\partial \vec{x}}(\vec{x}_{eq}; V)\right| = \left|\begin{matrix}\dfrac{\partial U}{\partial w_1} \\ \dfrac{\partial U}{\partial \varphi_1}\end{matrix}\right| (w_{1eq}, \varphi_{1eq}; V) = \left|\begin{matrix}0 \\ 0\end{matrix}\right|.$$

A local continuation method was implemented in Mathematica for tracing the equilibrium point coordinates at increasing voltage. The approach used to solve the problem is based on sweeping of the voltage, from the initial value V_0 toward increasing positive values. For each voltage value, the stability points are computed, by approximating the general potential in Taylor series around the previously computed equilibrium point $x_1 = \{w_{n,eq}[k-1], \varphi_{n,eq}[k-1]\}$. Wn denotes the normalized tip deflection $w_n = w_1/(L_y + t_y + d_y)$. This makes it possible to trace the evolution of the equilibrium point as function of V. For the computed values of $(w_{1,eq}, \varphi_{1,eq})$,

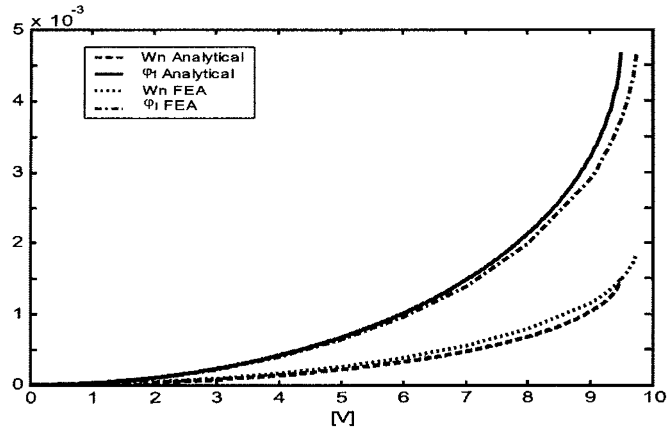

Fig. 3. Variation of the equilibrium point with applied voltage (both analytic model and finite element simulation).

the eigenvalues of the associated Hessian at that point can be computed. If any of these has a negative value, then the equilibrium point is unstable, and drawn as a separate line. Fig. 3 presents the results predicted from both analytical modeling and finite element simulations. It is interesting to note that pull-in occurs at $\varphi_1 \approx 4.5.10^{-3}$, which is equivalent to a deflection of movable electrode equal to $(\mathrm{L_y}+\mathrm{t_y}+\mathrm{d_y}).\sin(\varphi_1) \approx 0.72\ \mu$m. The maximum displacement operating range before pull-in occurs is of 36% the 2 -μm wide gap between the electrodes, which is about the same value as in the classic parallel plate case (1/3). As shown, the predicted pull-in voltage from the analytic model is at $\mathrm{V_{pi}} = 9.5$ V and in reasonable agreement with the FEM results.

III. Microstructure Fabrication

A modification on surface micromachining, a so-called epi-poly process, was used for the fabrication of 11 -μm thick single-side clamped 200 -μm long free-standing structures with electrode structures at the tip. Surface micromachining processes are very suitable for the fabrication of such free-standing beams on top of a silicon wafer. The disadvantages of the conventional surface micromachining in this application are twofold. First, it yields a polysilicon structural layer, which is expected to give an inferior long-term stability compared to crystalline silicon. Second, the 5–10 nm/min deposition rate of the conventional low-pressure chemical vapor deposition (LPCVD) limits the practical layer thickness to about 2 μm. Epitaxial growth at about 700 nm/min can be used to yield polysilicon layers on top of a dielectric layer with a thickness in excess of 10 μm, thus solving the second problem. Such a process is generally referred to as an epi-poly process [13], [14]. After deposition the thick polysilicon layer can be patterned using deep reactive ion etching (DRIE). Microstructures can subsequently be released by selectively etching the underlying dielectric sacrificial layer using the DRIE holes as access channel. The first concern remains. Part of this research is, therefore, to verify whether the use of polysilicon rather than crystalline material is actually an issue. Initial results presented in the next section do identify other sources as limiting factors.

A fabricated pull-in device is shown in Fig. 4. The device is basically a free-standing lateral beam anchored at one end (the base) only. The beam can be deflected by electrostatic actuation in the plane of the wafer using a voltage applied across parallel plate capacitors composed of two sets of electrodes located alongside the free-standing tip, with counter electrodes anchored to the substrate. The deflection can be measured using the differential sense capacitor located directly on top of the substrate and aligned with the square-shape electrode at the tip of the beam. These buried polysilicon electrodes are electrically isolated from the substrate and placed symmetrically on either side of a guard electrode placed directly underneath the axial direction of the undeflected beam. Finally, there are electrically isolated stoppers to limit the lateral motion. The electrodes beneath the movable structure are used for capacitive detection of the pull-in voltage. The readout circuit is based on a capacitor bridge with two active arms. The complication in the readout is the aF resolution requirement in the presence of pF parasitic capacitors.

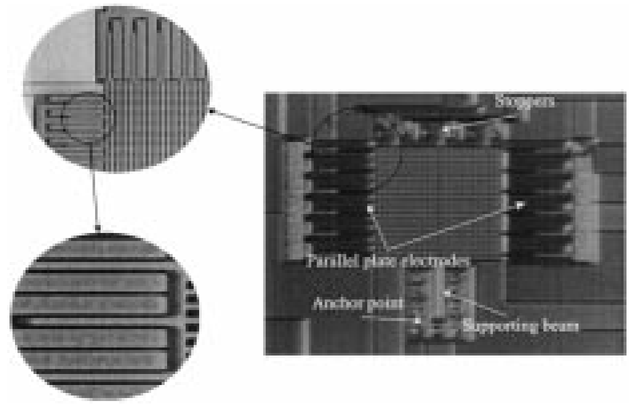

Fig. 4. Fabricated microstructure.

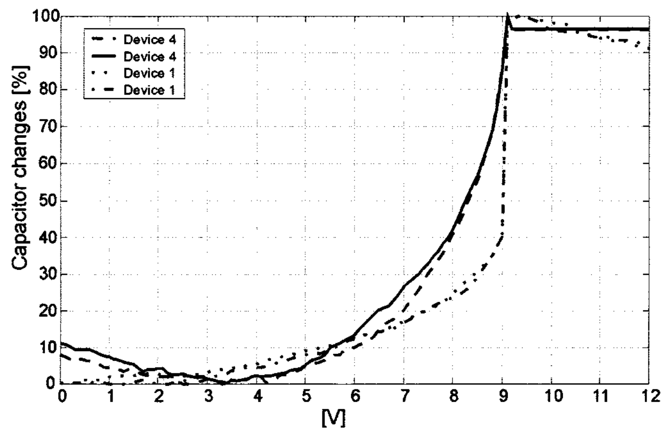

Fig. 5. Variation between several devices.

IV. Experimental Results

The measured pull-in voltage was about 9.1 V, which is near the predicted value from Mathematica model ($\mathrm{V_{pi}} = 9.5$ V). This difference is mainly due to the simplifying assumptions used and to process deviations, tolerances in the beam dimensions, and uncertainties in the value of the Young's modulus used in the numerical computation. Fig. 5 also indicates a profound quality difference between the devices. For proper operation as a voltage reference, the pull-in should be as abrupt as possible. Moreover, the effect should be reproducible. Clearly, de-

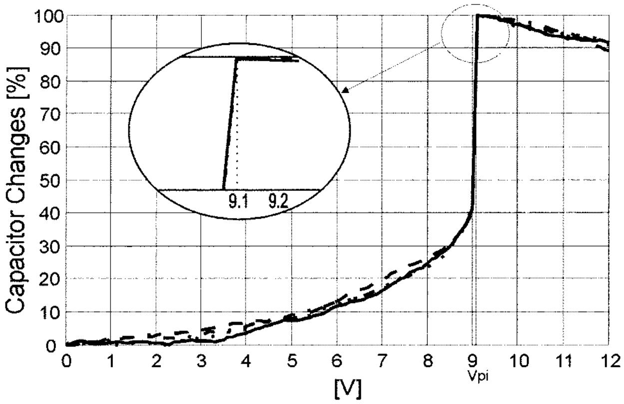

Fig. 6. Experimental result of a selected beam.

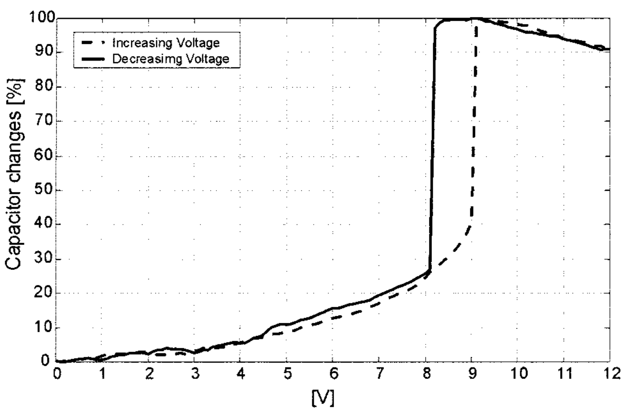

Fig. 7. Hysteresis in a pull-in microstructure.

vice #1 performs much better with respect to both requirements. The origins of these effects require further analysis. Fig. 6 shows the response of a selected device and Fig. 7 indicates that the devices also exhibit hysteresis. This property seriously complicates operation in a feedback loop.

V. CONCLUSIONS

The design and fabrication of a pull-in microstructure for application in metrology has been described in this paper. The feasibility has been demonstrated. First prototypes suffer from limited reproducibility and hysteresis. Experiments from another group on a metal-silicon electrode combination show a polarity dependent drift [6], [15]. This is not acceptable in I&M applications. The source of drift has been identified as charging of the (native) oxide of the polysilicon beam [16]. After coating the silicon with a metal of suitable work function, much better results are expected. The design of improved devices is forthcoming and measurements are scheduled to verify the long-term stability.

REFERENCES

[1] *Proc. Symp. Microtechnology in Metrology and Metrology in Microsystems*, Delft, The Netherlands, Aug. 31–Sept. 1 2000.

[2] B. P. van Drieënhuizen and R. F. Wolffenbuttel, "Integrated electrostatic RMS-to-DC converter using IC-compatible surface micromachining," in *Proc. Transducers*, Stockholm, Sweden, June 25–29, 1995, pp. 130–133.

[3] M. Klonz and T. Weimann, "Accurate thin-film multijunction thermal converter on a silicon chip," *IEEE Trans. Electron Devices*, vol. 38, pp. 335–337, Feb. 1989.

[4] G. de Graaf, M. Bartek, Z. Xiao, C. J. van Mullem, and R. F. Wolffenbuttel, "Bulk micromachined electrostatic RMS-to-DC converter," *IEEE Trans. Instrum. Meas.*, vol. 50, Feb. 2001.

[5] H. Seppä, J. Kyynäräinen, and A. S. Oja, "Micromechanical systems in electrical metrology," *IEEE Trans. Instrum. Meas.*, vol. 50, pp. 440–444, Apr. 2001.

[6] A. S. Oja, J. Kyynäräinen, H. Seppä, and T. Lampola, "A micromechanical DC-voltage reference," in *Conf. Dig. CPEM*, Sydney, Australia, May 14–19, 2000, pp. 701–702.

[7] M. Bartek, Z. Xiao, C. van Mullem, and R. F. Wolffenbuttel, "Bulk-micromachined electrostatic RMS-to-DC converter: Design and fabrication," in *Proc. MME*, Uppsala, Sweden, Oct. 1–3, 2000, pp. A14.1–A14.4.

[8] E. Cretu, L. A. Rocha, and R. F. Wolffenbuttel, "Using the pull-in voltage as voltage reference," in *Proc. Transducers*, vol. 1, Munich, Germany, June 10–14, 2001, pp. 678–680.

[9] H. A. C. Tilmans and R. Legtenberg, "Electrostatically driven vacuum-encap-sulated polysilicon resonators—Part II: Theory and performance," *Sens. Actuators A*, vol. 45, pp. 67–84, 1994.

[10] S. T. Cho, K. Najafi, and K. D. Wise, "Internal stress compensation and scaling in ultrasensitive silicon pressure sensors," *IEEE Trans. Electron Devices*, vol. 39, pp. 836–842, Apr. 1992.

[11] P. J. French, "Development of surface micromachining technologies compatible with on-chip electronics," *J. Micromech. Microeng.*, vol. 6, pp. 197–211, 1996.

[12] W. C. Tang, T.-C. H. Nguyen, and R. T. Howe, "Laterally driven polysilicon microstructures," *Sens. Actuators A*, vol. 20, pp. 25–32, 1990.

[13] M. Offenberg, F. Lärmer, B. Elsner, H. Münzel, and W. Riethmüller, "Novel process for in integrated accelerometer," in *Proc. Transducers*, vol. 1, Stockholm, Sweden, June 25–29, 1995, pp. 589–593.

[14] [Online]. Available: http://www.vdivde-it.de/mst/imsto/Europractice/Bosch/default.html

[15] J. Kyynäräinen, A. S. Oja, and H. Seppä, "Stability of micromechanical devices for electrical metrology," *IEEE Trans. Instrum. Meas.*, vol. 50, Feb. 2001.

[16] J. Wibbeler, G. Pfeifer, and M. Hietschold, "Parasitic charging of dielectric surfaces in capacitive MEMS," *Sens. Actuators A*, vol. 71, pp. 74–80, 1998.

Edmond Cretu (S'91–M'99) was born in Bucharest, Romania, in 1965. He received the M.Sc. degree in electronic engineering from the Polytechnic University of Bucharest in 1989. He is currently pursuing the Ph.D. degree at the Electronic Instrumentation Laboratory, Delft University of Technology, Delft, The Netherlands.

He was a Researcher at the Romanian Academy of Sciences and as an Associate Assistant at the faculty of Electrical Engineering of the Polytechnic University of Bucharest. Since March 2000, he has been with Melexis Belgium, where he is involved in the development of gyroscopes.

Luis Alexandre Rocha was born in Guimarães, Portugal, in 1977. In 1995, he began to study electronic engineering at the University of Minho, Minho, Porgtugal, where he graduated in 2000. Since February 2001, he has been pursuing the Ph.D. degree at the Electronic Instrumentation Laboratory, Delft University of Technology, Delft, The Netherlands. The topic of his research includes the study and design of MEMS for microinstrumentation.

Reinoud F. Wolffenbuttel (S'86–M'88–SM'97) received the M.Sc. and Ph.D. degrees from the Delft University of Technology, Delft, The Netherlands, in 1984 and 1988, respectively.

Between 1986 and 1993, he was an Assistant Professor, and since 1993, an Associate Professor, at the Laboratory of Electronic Instrumentation of the Delft University of Technology, where he is involved in instrumentation and measurement in general and on-chip functional integration of microelectronic circuits and silicon sensor, fabrication compatibility issues, and micromachining in silicon and microsystems, in particular. He was a Visitor at the University of Michigan, Ann Arbor, in 1992, 1999, and 2001, at Tohoku University, Sendai, Japan, in 1995, and at EPFL, Lausanne, Switzerland, in 1997.

Dr. Wolffenbuttel was the recipient of a 1997 NWO pioneer award. He served as General Chairman of the Dutch National Sensor Conference in 1996 and Eurosensors in 1999.