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**DEVELOPMENT AND APPLICATION OF HIGH-TEMPERATURE-  
APPLICABLE PIEZOELECTRIC FILM SENSORS**

by

**Barend R. Jooste**

**A DISSERTATION**

**Presented to the Faculty of  
the Graduate College at the University of Nebraska**

**In Partial Fulfillment of Requirements**

**For the Degree of Doctor of Philosophy**

**Major: Interdepartmental Area of Engineering (Chemical and Materials Engineering)**

**Under the Supervision of Professor Hendrik J. Viljoen**

**Lincoln, Nebraska**

**December, 1999**

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DISSERTATION TITLE

DEVELOPMENT AND APPLICATION OF HIGH-TEMPERATURE -  
APPLICABLE PIEZOELECTRIC FILM SENSORS

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# **DEVELOPMENT AND APPLICATION OF HIGH-TEMPERATURE-APPLICABLE PIEZOELECTRIC FILM SENSORS**

**Barend Rudolf Jooste, Ph.D.**

**University of Nebraska, 1999**

**Adviser: Hendrik J. Viljoen**

Piezoelectric transducers are used extensively as acoustic sensors and actuators in the non-destructive testing (NDT) of engineering structures and materials at room temperature. There is also a need for acoustic sensors that can operate at high temperatures, for example the monitoring of acoustic disturbances in gaseous combustion processes that cause combustion instability in the gas phase and structural vibrations in combustion apparatus. The sensors could be integrated into a smart control system to stabilize the combustion process and minimize structural vibrations. Another application is in an embedded sensor network for NDT of high temperature composite vessels.

Tantalum pentoxide ( $\text{Ta}_2\text{O}_5$ ) was investigated as a possible high temperature resistant piezoelectric material. Thin films of  $\text{Ta}_2\text{O}_5$  were deposited by reactive sputtering with and without substrate heating. Crystalline films were obtained by film deposition at



450°C and by annealing films deposited without substrate heating. Crystalline  $\beta$ -Ta<sub>2</sub>O<sub>5</sub> is formed at these conditions with either monoclinic or orthorhombic crystal structure, which is stable up to 1360 °C and piezoelectric. The piezoelectric response of thermally crystallized Ta<sub>2</sub>O<sub>5</sub> film was investigated qualitatively for different annealing temperatures. The piezoelectric response for Ta<sub>2</sub>O<sub>5</sub> films deposited in the crystallized form at 450°C were found to have a stronger piezoelectric response than thermally crystallized Ta<sub>2</sub>O<sub>5</sub> films and the piezoelectric constant,  $d_{z1}$ , of the film determined, based on a freely vibrating cantilevered beam technique. The technique could possibly be extended to measurement of piezoelectric properties of films at elevated temperatures.

- The constant  $d_{z1}$  was determined for Ta<sub>2</sub>O<sub>5</sub> film deposited at 450 °C, and for film subsequently exposed to 700 °C in air.

A spring-node model with simulation results is also presented for stress wave propagation in isotropic and transversely isotropic materials with or without piezoelectric properties for intact and flawed material. The model was applied to the impact-echo NDT technique for thick fiber composite materials where a piezoelectric film sensor is used. Experimental and theoretical sensor responses are compared.

**for KAREN and THEO**

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## ACKNOWLEDGEMENTS

I would like to express my sincere thanks to my adviser, Dr. Henk Viljoen, for all his guidance in my studies and for helping me to achieve independence and self-confidence in research. I would like to thank Globe Metallurgical Inc. and the South African Foundation for Research Development for the funding they supplied to make this project possible. I would also like to thank my loving wife, Karen and my wonderful son, Theo for all their love, warmth and patience throughout the completion of this work.

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**fiber composite plate**

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## LIST OF SYMBOLS

<u>Symbol</u>	<u>Meaning of Symbol and Units</u>
$A$	Surface area of electrode ( $m^2$ )
$C_{11}, C_{13}, C_{33}, C_{44}$	Stiffness constants in abbreviated subscript notation ( $N/m^2$ )
$C_{damp}$	Voltage lost due to damping (V)
$C_{fric}$	Voltage lost due to initial friction at beam release (V)
$C_{ijkl}$	Stiffness tensor ( $N/m^2$ )
$C_{loss}$	Total peak to peak voltage lost due to damping and initial friction (V)
$C_{kv}$	Kelvin-Voigt damping constant (internal damping) ( $kg/m.s$ )
$C_{kv,s}$	Kelvin-Voigt damping constant for uncoated beam ( $kg/m.s$ )
$C_{kv,sf}$	Kelvin-Voigt damping constant for beam coated with piezoelectric film ( $kg/m.s$ )
$C_v$	Viscous damping constant ( $kg/m.s$ )
$C_{v,s}$	Viscous damping constant for uncoated beam ( $kg/m.s$ )
$C_{v,sf}$	Viscous damping constant for beam coated with piezoelectric film ( $kg/m.s$ )
$D_b$	Flexural rigidity of beam ( $N.m^2$ )
$D_{b,s}$	Flexural stiffness of uncoated beam with piezoelectric film ( $N.m^2$ )
$D_{b,sf}$	Flexural stiffness of beam with piezoelectric film ( $N.m^2$ )
$d_{centroid}$	Shortest distance between the bottom of the beam and the beam centroid (m)
$d_f$	Piezoelectric film thickness (m)
$D_{FN}$	$d_s - d_{centroid}$ (m)

$D_{id}$	Initial displacement distance of cantilevered beam tip (m)
$D_s$	Thickness of cantilevered beam (m)
$D_x, D_y, D_z$	X, y and z components of the dielectric displacement vector (charge displacement vector) ( $C/m^2$ )
$d_{z1}, d_{z3}, d_{z4}, d_{z6}$	Piezoelectric stress constants defined in figure 2.1 ( $C/N$ )
$E$	Young's modulus ( $N/m^2$ )
$E_f$	Young's modulus of piezoelectric film ( $N/m^2$ )
$E_L$	Young's modulus in fiber direction ( $N/m^2$ )
$E_T$	Young's modulus in transverse direction ( $N/m^2$ )
$E_s$	Young's modulus of substrate ( $N/m^2$ )
$e_{13}, e_{15}, e_{33}, e_{31}$	Piezoelectric strain constants ( $N/C$ )
$E_s$	Young's Modulus of uncoated beam ( $N/m^2$ )
$E_z$	Electric field in the z-direction ( $V/m$ )
$f_{exp,s}$	Experimental frequency of uncoated cantilevered beam with small piezoelectric sensor (Hz)
$f_{exp,sf}$	Experimental frequency of cantilevered beam coated with a piezoelectric film on one side (Hz)
$G_{LT}$	Shear modulus of unidirectional fiber composite ( $N/m^2$ )
$H$	Height of material section modeled by SNM (in z-direction) (m)
$I$	Moment of inertia ( $m^4$ )
$I_f$	Moment of inertia of piezoelectric film ( $m^4$ )
$I_s$	Moment of inertia of substrate ( $m^4$ )
$I_{sf}$	Moment of inertia of cantilevered beam coated with piezoelectric film ( $m^4$ )
$k_p, k_s$	Diagonal spring constants in the SNM ( $N/m$ )