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Resonance Analysis of High Temperature Piezoelectric Materials for Actuation and Sensing

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ABSTRACT

The current NASA Decadal mission planning effort has identified Venus as a significant scientific target for a surface in-situ sampling mission. The Venus environment represents several extremes including high temperature (460^{o}C), high pressure (~9 MPa.), and potentially corrosive (condensed sulfuric acid droplets that adhere to surfaces during entry) environments. This technology challenge requires new actuator and sensor designs that can withstand these extreme conditions. In addition a variety of industrial applications could benefit from an extended operating temperature range of actuators and sensors. Piezoelectric materials can potentially operate over a wide temperature range reaching as low as –270^{o}C to as high as +650^{o}C. Single crystals, like $LiNbO_3$, have a Curie temperature that is higher than +1000^{o}C. In order to investigate the feasibility of producing actuators/sensors that can operate under these conditions we have initiated a study of the properties of a variety of piezoelectric materials in the temperature range 25^{0}C to 500^{0}C. These piezoelectric materials were chosen because they are solid state and can be designed as actuators to provide high torque, stroke, and speed. However the feasibility of this critical actuation capability has never been demonstrated under the extreme conditions mentioned above. We will present the results of our measurements on a variety of piezoelectric materials that can be operated at temperatures above 460^{o}C. The data for small signal resonance analysis (ring, radial and thickness extensional modes) of disk and ring samples made of BST-PT and BMT-PT (TRS Technologies Inc.) and Bismuth Titanate BT (Ferroperm Piezoceramics A/S, Sinoceramics) as a function of the temperature will be presented.

Keywords: High Temperature Piezoelectric, Curie temperature, piezoelectric response, mechanical Q, Bulk Acoustic Waves Devices

1. INTRODUCTION

Future NASA exploration missions of the New Frontier program will involve in-situ sampling and analysis under extreme environmental conditions.. These missions require actuators that can exert sufficiently high strokes, torques, and forces while operating at the related harsh conditions. Venus is one of the targets of this program and a mission to this planet has been included in the NASA Decadal Planning effort. The environment on Venus poses a challenge to the existing actuation technology and there are no commercially available motors that can operate at its ambient temperature of 460 ^{o}C. Piezoelectric materials have the potential to operate at this temperature level and can produce the stroke and force that is required to operate the needed mechanisms. Examples of the types of actuators that can be manufactured from piezoelectric ceramics are shown in Figure 1. Ultrasonic drills, corers and rock abrasion tools have be designed, fabricated and tested at JPL. In addition rotary motors and peristaltic pumping mechanisms have been developed. In order to determine if these materials can be used to build actuators which can operate at or above 450 ^{o}C we have initiated a study to determine the feasibility of these emerging high temperature piezoelectric materials in support of this NASA need. A series of piezoelectric samples with Curie temperatures greater than 400^{o}C were obtained. Small signal resonance studies were done on the thickness, radial or ring modes of these samples. The equations used in the analysis are shown in Table 1. In many applications shown in Figure 1 the mode of actuation is the length extensional (LE) mode. These resonators are typically small rods with a very small capacitance and it is much

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more difficult to correct for parasitic capacitance of the sample holder. However, the thickness, radial and ring resonances have much larger capacitance and these modes were chosen to monitor the temperature dependence.

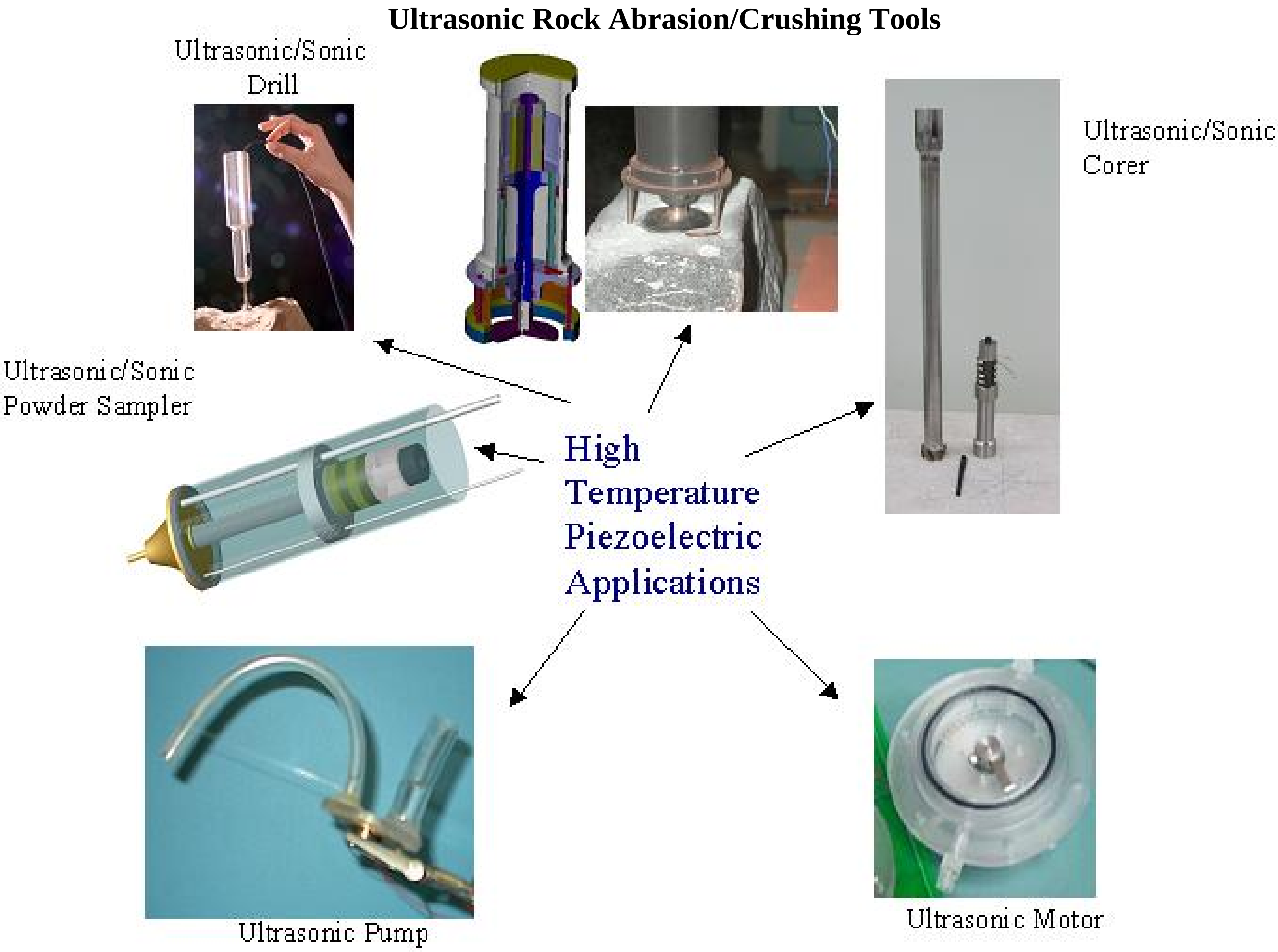

Figure 1. A variety of actuators mechanisms that could operate at Venus temperatures if suitable piezoelectric ceramics could be found.

The measurements of these modes were fit as follows: for the ring and thickness modes Smits'[1,2] method was used, whereas a method published earlier[3] was used for the radial mode. In general, at least three independent coefficients (a dielectric, elastic and piezoelectric coefficient) can be determined from each resonance with the exception of the radial mode where Poisson's ratio can also determined. The minimum number of coefficients determined from each mode is also shown in Table 1. A number of additional coefficients can be determined from these coefficients including the piezoelectric e_{33} and h_{33} values for the thickness mode and all of the radial coefficients for the radial mode.

Table 1. The resonance modes and coefficients used to compare the HT samples

Resonance mode	Equation	Coefficients determined

Thickness Extensional TE	$Z = \frac{l}{i\omega A\boldsymbol{\varepsilon}_{33}^{S}}\left(1-\frac{\boldsymbol{k}_t^2\tan\left(\frac{\omega}{4\boldsymbol{f_p}}\right)}{\frac{\omega}{4\boldsymbol{f_p}}}\right)$	$\boldsymbol{\varepsilon}_{33}^{S}, \mathbf{k}_t$ *and* $\mathbf{c}_{33}^{D}$
Radial Extensional (RE)	$\mathbf{Y} = \frac{-i\omega\boldsymbol{\varepsilon}_{33}^{\mathbf{P}}\pi a^2}{d}\left[\frac{2\left(\mathbf{k}^P\right)^2}{\left[1-\boldsymbol{\sigma}^P-\mathbf{J}\left(\frac{\omega a}{\mathbf{v}^P}\right)\right]}-1\right]$	$\mathbf{s}_{11}^{E}, \mathbf{s}_{12}^{E}, \boldsymbol{\varepsilon}_{33}^{T}, \mathbf{d}_{13}$ $\mathbf{k}_P$, σ_P
Ring Breathing (RB)	$Y = \frac{i\omega A}{t}\left(\boldsymbol{\varepsilon}_{33}^{T}\left(1-k_{13}^2\right)+\frac{\boldsymbol{\varepsilon}_{33}^{T}k_{13}^2\boldsymbol{\omega}_r^2}{\boldsymbol{\omega}_r^2-\boldsymbol{\omega}^2}\right)$	$\mathbf{s}_{11}^{E}, \boldsymbol{\varepsilon}_{33}^{T}, \mathbf{d}_{13}$

2. EXPERIMENTAL

Samples of the various high temperature piezoelectric materials (BS-PT, BMT-PT, Pz46, and B8613) were connected electrically to high temperature feed-throughs using alumina insulation tubing and chromel wires. The wires were affixed using silver paste. The samples were heated using a General Signal Blue M furnace (4717 /RT- 715°C) with a Eurotherm 808 Temperature controller as shown in Figure 2. To establish a baseline for the data measurements of the thickness and ring or radial resonances for these samples along with a Navy III sample were made at room temperature prior to heating. The resonance spectra for these samples are shown in Figures 3-6. The temperature in the furnace was ramped up at 50 degree C intervals and the measurements of each of these modes' spectra were repeated. At each temperature short and open circuits feed-through were measured to determine the required corrections for the effect of the parasitic impedance of the holder. The impedance was measured using an HP4192a Impedance Analyzer. The sample dimensions were determined using a digital set of Vernier caliper while the density was taken from the manufacturers' datasheets. Pictures of the experimental setup along with a schematic are shown in Figure 1 below.

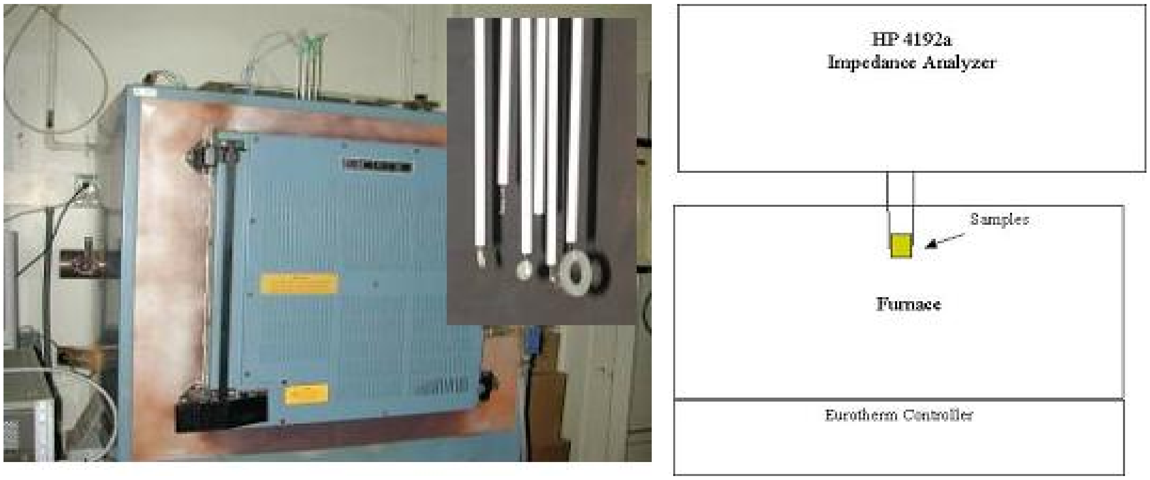

Figure 2 Experimental setup for the high temperature tests. Alumina Feed-throughs are shown in the inset picture.

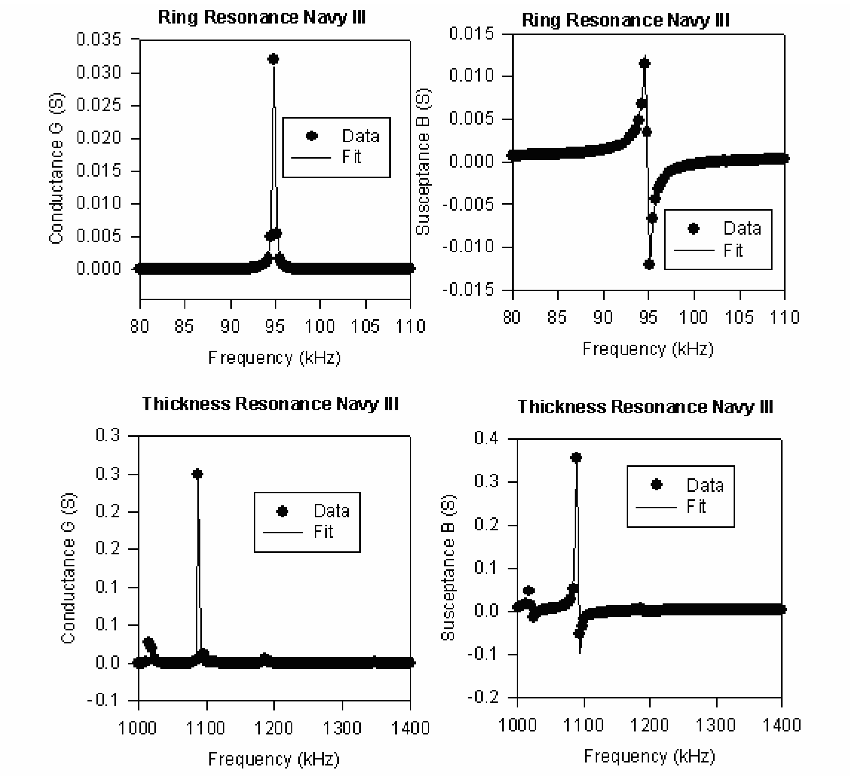

Figure 3. Data from ring and thickness resonance spectra for the baseline material used in the USDC (Navy III)

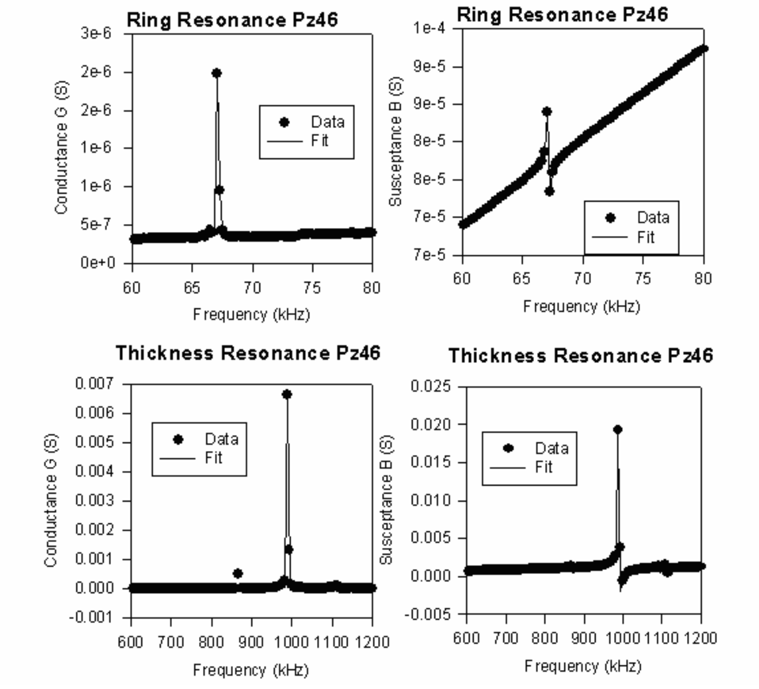

Figure 4: Data from ring and thickness resonance spectra for the Ferroperm high temperature Material (PZ46)

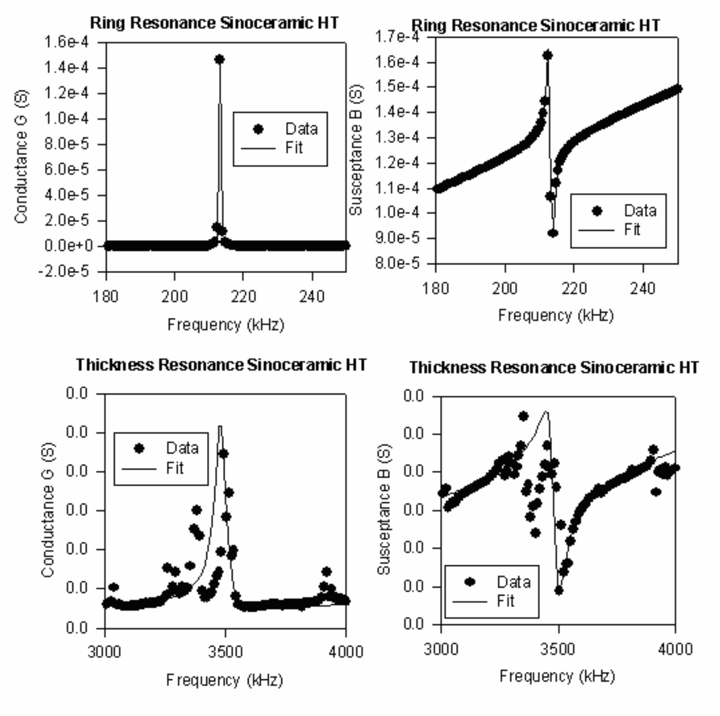

Figure 5. Data from ring and thickness resonance spectra for the SinoCeramic high temperature Material (B8613)

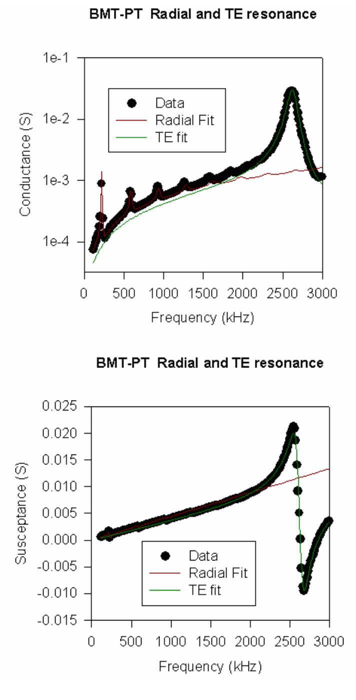

Figure 6. Data and fits from radial and thickness resonance spectra for the TRS high temperature Material (BMT-PT)

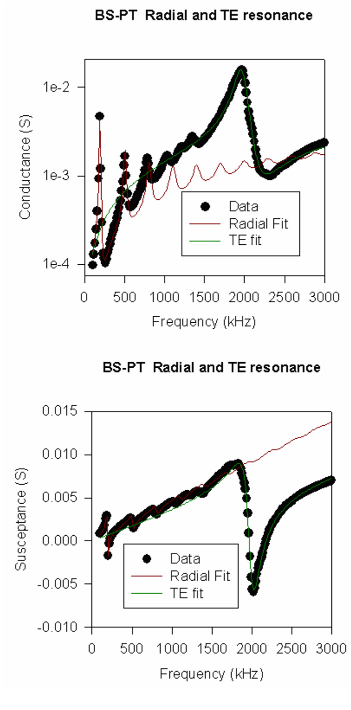

Figure 7. Data and fits from radial and thickness resonance spectra for the TRS high temperature Material (BS-PT)

The coefficients are extracted from the room temperature spectra shown in Figures 3-7 are listed in Table 2, where a wide variety of material properties are shown for these high temperature materials. The BS-PT and BMT-PT samples show piezoelectric activity of the same order as the Navy III material, which is used as a standard material for high power actuators. Although these materials have piezoelectric activity of the same order the mechanical and electrical losses are about an order of magnitude higher than the losses in the Navy III material. The Bismuth Titanate samples (Pz46 and B8613) have piezoelectric activity that is considerably lower than the Navy III material however the losses are lower. Ideally, high piezoelectric activity and low losses are needed when produce high frequency actuation mechanism (Horns, stacks, motors, etc). The mechanical Q reported for the PZ46 and B8613 high Q materials are likely lower than actual values due to wire contact damping the resonance.

3. Properties versus Temperature

The thickness mode resonance data for the piezoelectric samples is shown in Figure 8, whereas the ring and radial mode data for the samples is shown in Figure 9. The Bismuth Titanate samples (Pz 46, B8613) were found to be stable up to 500°C while the BMT-PT (470 °C) and the BS-PT(440 °C) samples were depoled between 450°C and 500°C, and 400°C and 450°C, respectively.

Table 2. Comparison of the room temperature material coefficients of the HT materials with a Navy III material (Channel 5800).

Material Property	Navy III	BS-PT	BMT-PT	Pz46	B8613
$\mathbf{s}_{11}^{E}$ (10^{-11}m^2/N)	0.94	1.27	1.01	0.84	1.36
$\boldsymbol{\varepsilon}_{33}^{T}/\varepsilon_0$ (#)	1020	1330	860	121	90
$\mathbf{d}_{13}$ (pC/N)	111	136	49	1.3	4.6
$\mathbf{k}_P$ (#)		0.59	0.29		
σ_P (#)		0.27	0.24		
e_{33} (C/m^2)	11.1	12.2	12.8	2.1	2.6
$\mathbf{c}_{33}^{D}$ (10^{11} N/m^2)	1.62	1.46	1.91	1.20	1.28
$\mathbf{k}_t$ (#)	0.39	0.47	0.44	0.19	0.23
$\mathbf{k}_{13}$ (#)	0.38			0.014	0.044
tanδ (at RE or RB mode frequencies)	0.012	0.1	0.12	0.004	0.0024
Mechanical Q (From $\mathbf{s}_{11}^{E}$)	320	14	23	1580[*]	590[*]

[*] Likely decrease from reported values due to damping of resonance by wire contact.

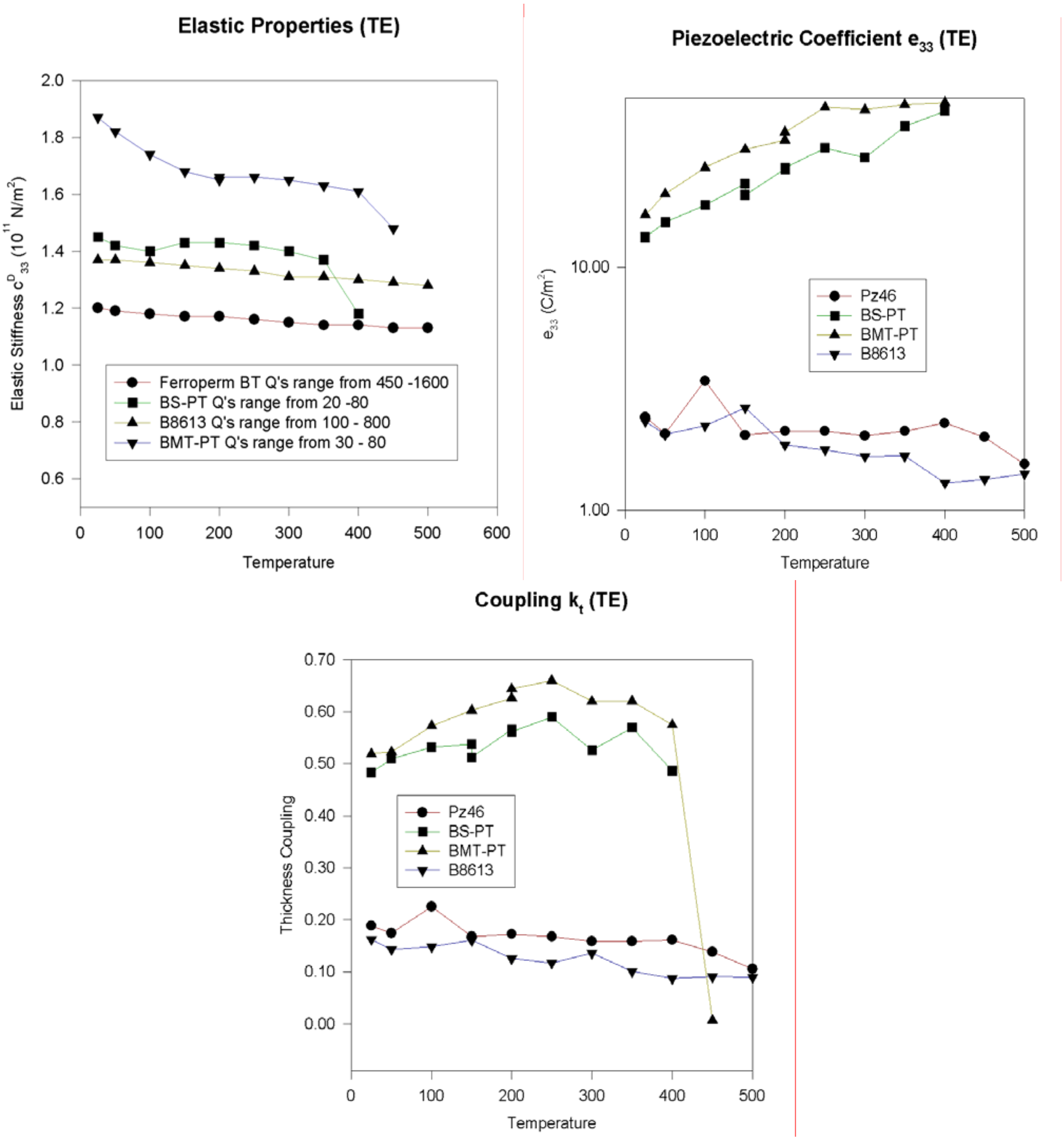

Figure 8. The thickness mode stiffness, piezoelectric coefficient and coupling as a function of temperature for the four materials studied

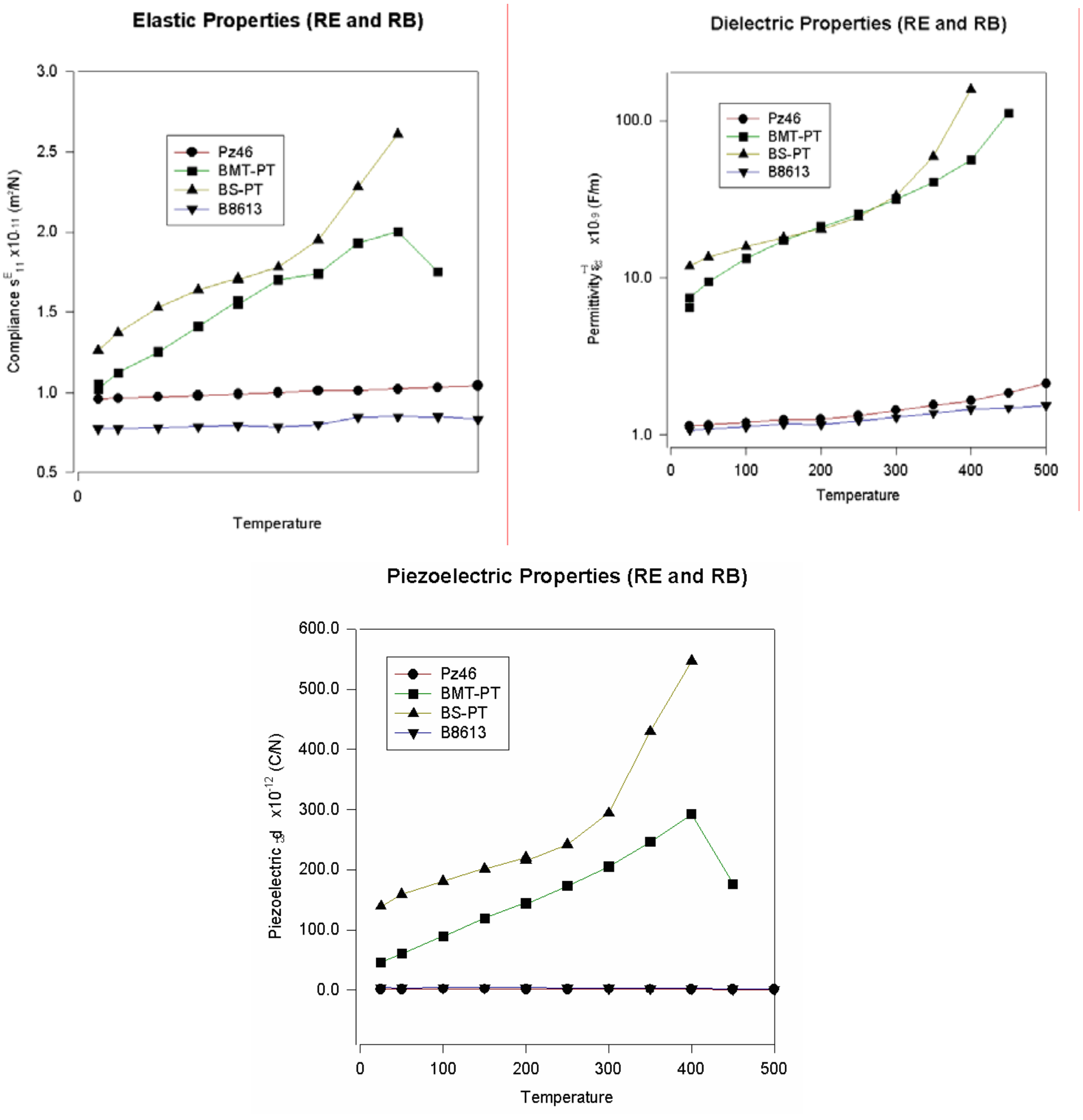

Figure 9. The radial or ring mode compliance, piezoelectric coefficient and coupling as a function of temperature for the four materials studied

4. ELECTROSTRICTION

An attempt was made to try to stimulate a biased electrostrictive response in the de-poled materials (BMT-PT, BS-PT) at 450°C and 500°C. A biased piezoelectric resonance could not be found in the spectra, however it is believed that due to minimum field that could be applied it is unlikely that a measurable response could be recorded. Isolation circuitry, such as the one shown in Figure 10, may need to be built in order to investigate this effect at reasonable field levels.

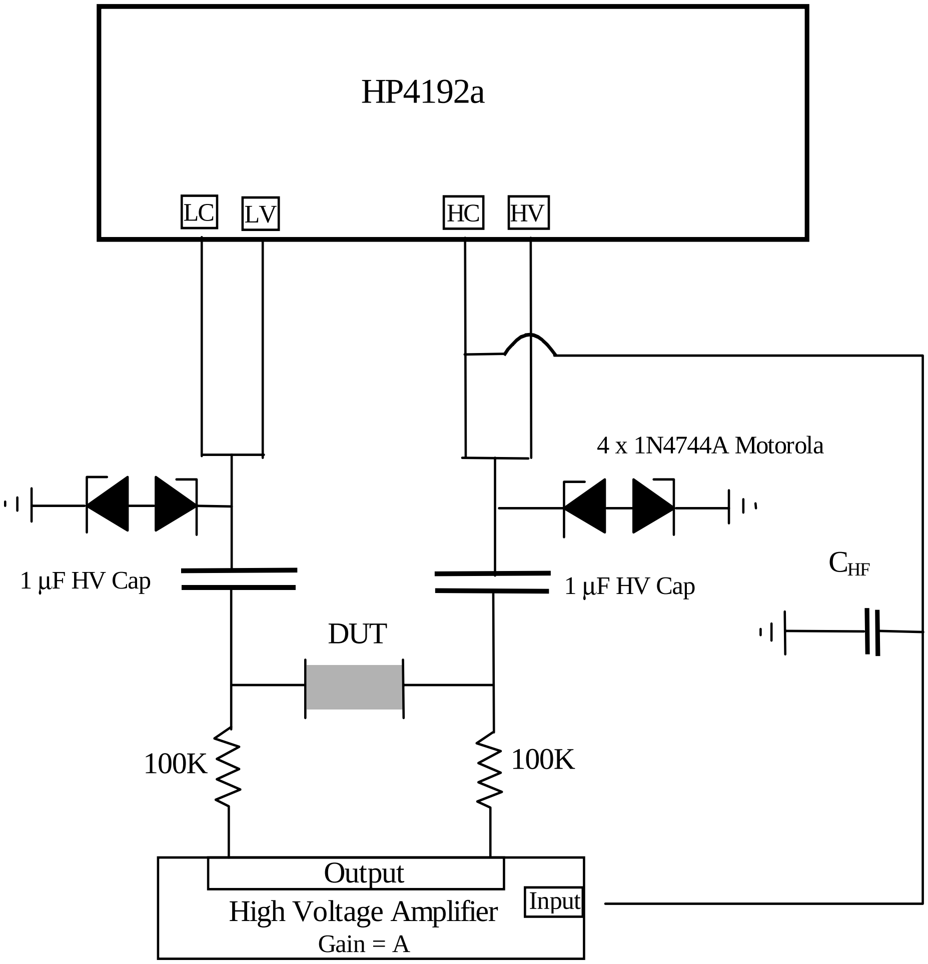

Figure 10: Schematic diagram of the isolation circuitry required for the DC biased resonance measurement at high fields based on earlier work[4].

5. CONCLUDING REMARKS

A study was initiated at the JPL's NDEAA Lab to establish piezoelectric actuation capability to operate at the ambient temperature of Venus ((460°C). A series of resonance tests were made activating high temperature piezoelectric samples at the thickness and radial or ring modes and the spectral response was measured. It was determined that the Bismuth Titanate samples (Pz 46 supplied by Ferroperm, B8613 supplied by Noliac) are stable up to 500°C whereas the BMT-PT and the BS-PT samples were depoled between 450°C and 500°C, and 400°C and 450°C, respectively. Although these materials have piezoelectric activity of the same order as in the PZT type Navy III material, the mechanical and electrical losses are about an order of magnitude higher. The Bismuth Titanate samples (Pz46 and B8613) have piezoelectric activity that is considerably lower than the Navy III material however their losses are generally lower. Ideally, high piezoelectric activity and low losses are required to produce high frequency actuation mechanisms (Horns, stacks, motors, etc).

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