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Study of the Thermal Behaviour of PN Thermoelectric Couples by Laser Probe Interferometric Measurement.

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Abstract.

The purpose of the present paper is to provide experimental data related to the temperature distribution within thermoelectric devices(TE). Moreover our aim is to get this knowledge for a dynamic temperature response of the device.

We propose a non-contact optical measuring method, based upon very high-resolution interferometry, to map temperature effects upon the surface of running thermoelectric devices.

The Peltier sources within the device generate thermal waves associated to heat transport. These waves interfere when AC current is driven through the device. The interferences are clearly observed in our measurements, showing how heats flows from different sources merge.

The measuring method can be used to check material properties which in turns allows to optimize contact design.

1.Introduction.

Thermoelectric phenomena, as the Seebeck and Peltier effects, have been widely used over the last 30 years in devices for energy generation and cooling purposes, [1]. If an electric current passes through a junction of dissimilar materials heat is absorbed or dissipated according to the current direction, by means of the Peltier effect. Conversely, a temperature gradient along the thermoelectric material will generate an E.M.F.: the Seebeck effect.

Optical instruments allow studying the thermal behaviour of electronic components in a very appropriate manner [2,3].

Optical probing is non-contact, has a high lateral resolution (in our case less than 1 μm), can be used upon running devices without perturbation and allow to follow fast phenomena.

We have used an optical laser probe to study the harmonic thermal behaviour of thermoelectric PN couples. Many thermal phenomena take place simultaneously in such devices. Heat sources and heat dissipation are present.

The harmonic regime produces an interesting dynamic steady state of the response offering as we will show, many information upon the thermal phenomena taking place in the device.

When the current is modulated, thermal waves are generated inside TE devices; one can see the junction as a well-localised periodic heat source. The temperature at the junction varies with the current frequency. To this periodic temperature variation is associated a thermoelastic surface wave, which is attenuated as it propagates along the material surface from the source.

In a single PN thermoelectric couple, we differentiate three Peltier heat sources; at the PN junction heat is for example absorbed for a given current direction, whereas at the wire-semiconductors junctions heat is then released. For AC current excitation, phase opposed thermal waves are generated, they propagate from the sources one toward the other and interfere. The interference pattern depends upon the temperature amplitude at the source points and the thermal diffusivity of the materials.

We have chosen to use an interferometric laser probe to study the thermal response of the TE device mainly because provides absolute very reliable results. We have a long experience in temperature through thermal expansion measurements with laser probes [4]. In practice, surface displacement corresponding to thermal waves in a material are much easier to measure than the corresponding temperature changes.

2.PN Thermoelectric Couple.

The sample is composed of a single junction of N and P-doped Bi_2Te_3, (fig.1) and two wires provide contacts for the current source. The couple has been moulded in an epoxy resin in order to fix it, and it has been polished to optical quality, normal to one of the sample faces, so as to obtain a good surface quality for the laser probe measurements.

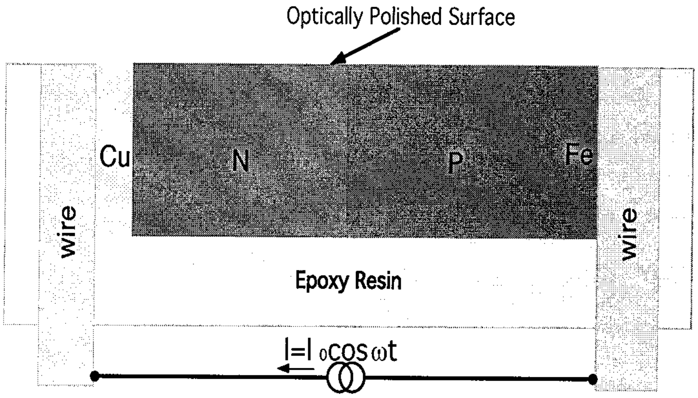

Fig.1 The sample: lateral view of cross section.

3.Interferometric Laser Probe.

The instrument used to perform the surface normal displacement measurements is a Michelson interferometer (fig. 3), which transfer function depends on the path difference between two laser beams.

A He-Ne laser beam is separated in two by means of a beam splitter (**Cs**) and each beam travels twice his path length repectively **ls** and **lr**. They recombine at the beam splitter output and interfere at the photodetector. The light intensity at

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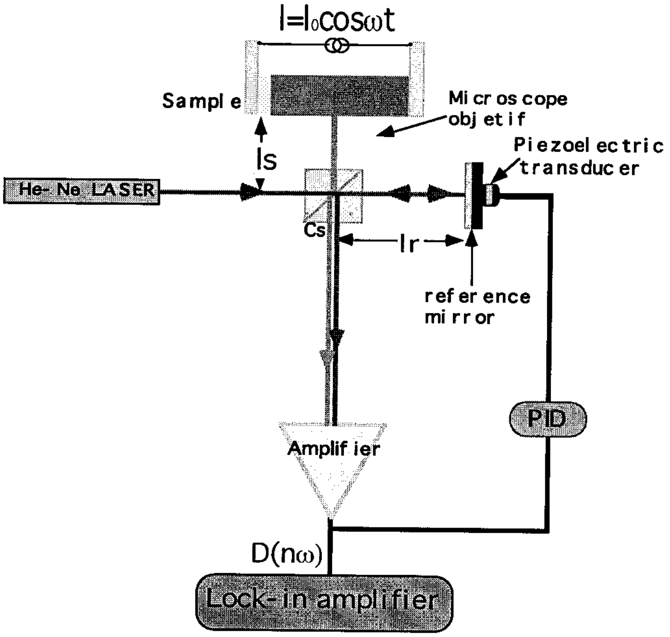

Fig. 2 Principle of the Method

the photodetector depends upon the path difference.

The distance ls is modulated by the normal surface displacement of the running thermoelectric couple. The distance lr is adjusted by a PID controller by means of a piezoelectric transducer, in order to maintain the operation at a maximal sensibility point of the interferometer transfer function.

This allows a direct absolute measurement of the displacement providing a calibration procedure that has been done. A.15 fm (10^{-15}m) sensibility is obtained in harmonic regime. The method takes advantage of a low noise amplifier and a lock-in amplifier and a stabilised laser source(fig.2). The lock-in amplifier allows also to measure higher order harmonics of the signal **n→(1-7).**

3.Surface waves

The Peltier heat absorbed or released at the junctions is proportional to the current according to the well known equation:

$$Q_{peltier}=\alpha_j IT \qquad \rightarrow(1)$$

Where the index α_j is the Seebeck coefficient of the couple, I is electric current and T is the junction temperature, j denotes the corresponding junction. On the other hand, the Joule heat is proportional to the square of the current:

$$Q_{joule}=RI^2 \qquad \rightarrow(2)$$

Where R is the electric resistance.

In the frequency domain, one can then expect a Peltier contribution to the local temperature variation at the excitation frequency and a Joule one at twice this frequency.

The Joule effect is a volumetric effect in the sample, (excepting for the contact resistances); in contrast, the Peltier effect is well localised, at the three junctions: Copper-N, NP, and P-Iron Junctions. The metallic junctions Cu-wire and Iron-wire will be ignored as the Peltier coefficients of these junctions can be neglected in comparison with the other ones.

The propagation of the Peltier heat flux in the sample produces an oscillating temperature field at each point on the surface in the vicinity of the junctions. The thermal properties of the materials determine the amplitude and the phase of the temperature variation for the given frequency at a given location on the surface of the sample.

Thermal expansion always accompanies temperature variations. The surface has also a normal displacement at the same frequency as the Peltier heat source.

This displacement is well fitted by the following expression:

$$D(x,\omega) = D_0 e^{-\delta(x-x_0)} \cos(\omega t-\beta(x-x_0)-n\pi) \rightarrow (3)$$

where D_0 is the displacement amplitude at the source (junction), x_0 is the position of the source upon the x-axis (dashed line in fig. 3) , ω is the current pulsation. Number n is an odd integer for the PN junction and even for the end junctions, as they are of opposite phase heat sources. δ^{-1} and β are coefficients proportional to the square root of thermal diffusivity. We have performed the profile measurements along the dashed line in fig.3 as the Peltier sources can be considered as planar sources, uniform in a plane perpendicular to x.

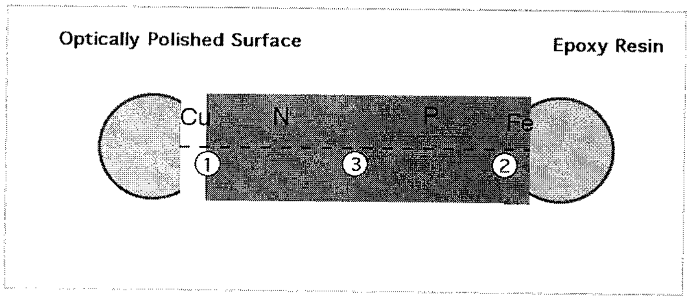

Fig. 3 Measurement Points.

As the displacement waves of the metal junctions and the PN junctions are phase opposed (see fig.4), the interferences will be destructives. The interference minima points values will depend upon the heat sources amplitude ratio and the thermal properties of the materials.

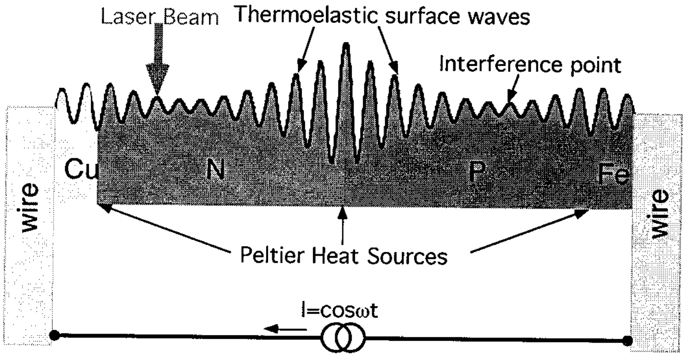

Fig.4 The sample: thermal waves generation.

5. Measurements.

5.1Displacement Current Law

Measurements have been made at different points of the sample along the dashed line shown in fig. 3. We have first studied the amplitude displacement as a function of the current at points numbered 1, 2 and 3 in fig. 3. A 7 Hz sine wave current feeds the sample. The displacement axis is in nanometers. A linear dependence is observed that is characteristic of the Peltier effect (see fig. 5).

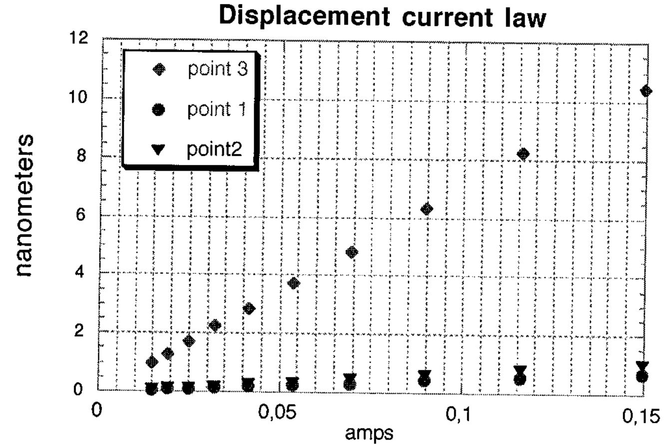

Fig. 5 Current vs. Displacement (rms) at three different points.

5.2 Bode Diagrams

Displacement measurements as a function of frequency were upon the junctions numbered fig. 4. Results are shown in fig. 6 for the displacement amplitude and fig. 7 for the displacement phase.

5.2.1 Displacement Modulus

The surface displacement frequency response decreases with frequency. As expected, the PN junction deformation is more important than the one at the ends, about ten times greater.

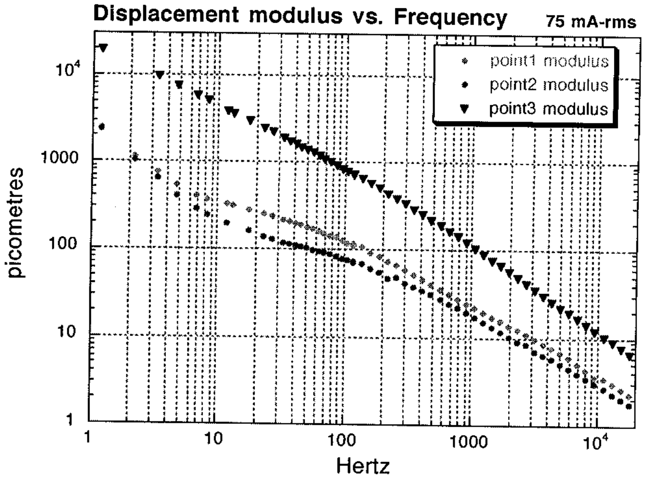

Fig. 6 Displacement Modulus

Two factors influence this dissymmetry: PN Peltier heat ratio is about two, according to the respective Peltier coefficients. Moreover, the Peltier Heat at the PN junction is "confined" due to the small Bi_2Te_3 thermal conductivity, whereas at the sample ends the heat is mostly dissipated through the metal layers and wires whose thermal conductivities are about a 100 factor greater than the semiconductor's ones. This explains the one-decade difference between the central and end junction thermal expansion.

5.2.2 Displacement phase

Phase response in the Bode diagram of fig. 7 shows the phase opposition between the PN and ends junction displacements. For low frequency the end phase of the displacement gets close to the PN phase. This can be explained by the propagation of the thermoelastic waves. Indeed, the attenuation of the thermoelastic wave becomes lower as frequency gets lower. In other words, the wave diffusion length increases, and the PN wave "dominates" the end ones. At high frequencies, near 10 kHz, the diffusion length of thermal waves is smaller than the dimensions of the sample. The heat fluxes generated at the junctions are too attenuated when they cross the semiconductors and reach the other junction to have a significant influence.

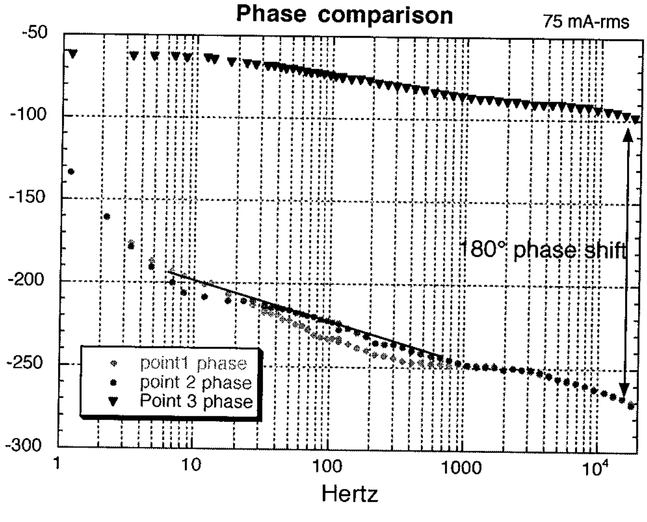

Fig. 7 Displacement phase

5.2.3 Joule Contribution to the local temperature.

We have tried to measure the second harmonic contribution **to the displacement** which is due to the Joule effect, but it was negligible in comparison with the Peltier contribution at this current value. Measurement at high current must be done in the future for make come out the influence of the Joule effect, this will be done in future work.

5.3 Displacement Profile

Fig. 8 shows the modulus of the normal displacement along the whole sample including the metallic layers for a 150 mA, 7 Hz current excitation of the sample. X axis is in micrometers.

Frequencies as low as 7 Hz are needed in order to be able to observe propagation over long distances (about 1mm in this case). If we look at the PN junction, we observe for positive and negative x a quasi-exponential decay of the surface displacement amplitude. This decay increases as we come close to the end sources, there, a mixing of thermal waves occurs and their phase-opposed nature makes them interfere.
It is clear that the PN wave dominates over the ends waves.
An interesting phenomenon is observed at the metallic layers: at the copper side, the wave is not attenuated in the metal, as it is the case in the iron layer. The ratio of the thermal diffisivities ($a_{Cu}/a_{Fe}\approx 4$) explains this dissymmetry.

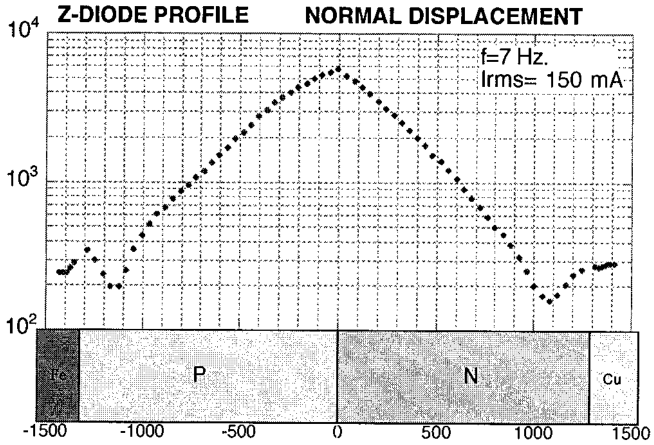

Fig. 8 Normal displacement profile

5.3.1 Thermal waves interferences

The data corresponding to the N-doped semiconductor has been taken in the fig. 9. A curve fitting procedure gives the next expression for the displacement in this material:

$$D(x) = 5870e^{(-3.05e-3-j8.2e-4)x} - 378e^{(-3.05e-3-j8.2e-4)(x-1286)}$$

x is expressed in µm
This corresponds to the complex representation of the superposition of two exponentially attenuated periodic sources spatially parted by 1286 µm. The amplitudes ratio at the origins is about 15.

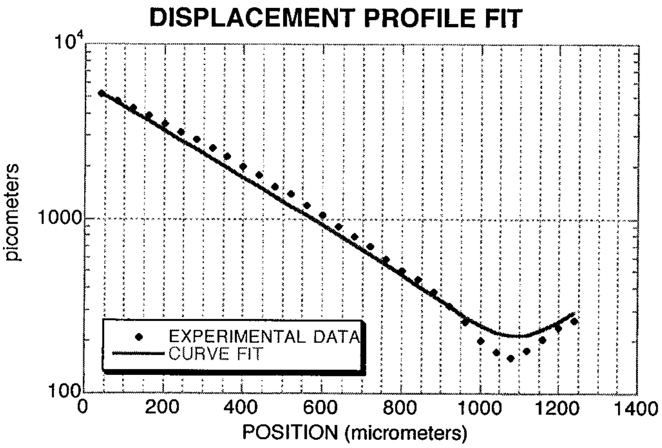

Fig. 9 Thermal Interferences Fit

Conclusions.

One can expect that good contacts at the junctions would generate a weak Joule contribution to the local temperature and thermal expansion. In addition, in optimised thermoelectric materials the joule contribution and diffusion length would be minimised. The Peltier contribution would be adversely affected by bad contacts. A Normal displacement-contact quality correlation is to be found.
Using optical laser probe techniques gives an original glance upon thermoelectric devices, interesting phenomena has been observed, as the generation of thermoelastic waves. Physical property characterisations could be the further applications for optical techniques.
This kind of technique for thermal characterisation presents several advantages with respect to well-known temperature measurement by thermocouple. It is non-contact, then there is not heat leakage as in thermocouple measurements [1]. Additionally, optical laser probe allows measurements with a micrometric lateral resolution, mapping the whole thermoelectric couple.

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