Integrated Thin-Film Micropotentiometers

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Abstract— **Integrated micropotentiometers, new devices fabricated with thin-film technology and the micromachining of silicon, have been developed for the accurate determination of ac voltage from 1 to 200 mV at frequencies from audio to 1 MHz and with the potential for higher frequencies.**

I. INTRODUCTION

MICROPOTENTIOMETERS are used as millivolt and microvolt standards at frequencies from 10 Hz to 1 GHz. Conventional micropotentiometers [1], [2] contain UHF type, single-junction thermoelements and radial, film output resistors with very small inductance in series with the thermoelement heater (see Fig. 1). Thermal voltage converters have been used to calibrate micropotentiometers at about 200 mV from 10 Hz to 30 MHz [3], [4], while lower voltage ranges are characterized by step-down methods. Recently, the 3σ uncertainties for 100 mV have been reduced at NIST from about 1000 ppm to 50 ppm at 100 kHz and from 1000 ppm to 250 ppm at 1 MHz. The 3σ uncertainty for 10 mV has been reduced from 1000 ppm to 200 ppm at 100 kHz.

Multijunction thermal converters (MJTC's) have very small ac-dc differences, good square law response, and high output emfs, and are used in very high-accuracy ac-dc difference metrology from audio frequency up to 100 kHz. MJTC's have been traditionally fabricated from wire heater resistors and thermocouples. Recently, MJTCs using thin-film photolithography, thick-film mounting substrates, and micromachining of silicon [5]–[7] have been developed to measure ac voltage and current. For this project, multilayer, thin-film MJTC's and thin-film output resistors have been fabricated as an integrated structure on the same silicon chip to form an integrated, thin-film micropotentiometer. The thin-film MJTC is used as a current sensor to set the ac current accurately in terms of a dc current. The ac or dc current passes through the thin-film output resistors which have small ac-dc differences to produce ac or dc millivolt outputs with small ac-dc differences. The low-level ac voltage can then be determined from a measurement of the dc output voltage and the micropotentiometer's ac-dc difference.

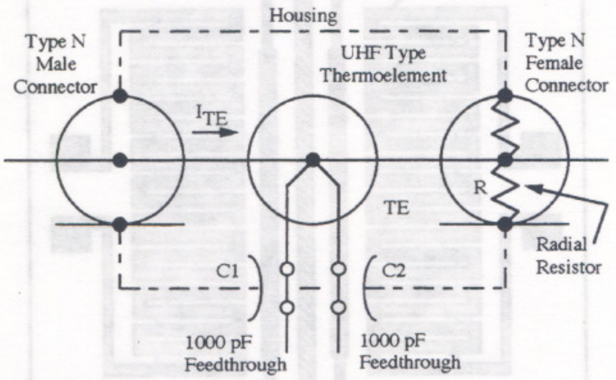

Fig. 1. Conventional micropotentiometer.

In thin-film multilayer MJTC's, the thin-film heater and thermocouple hot junctions are supported by a thin, multilayer dielectric membrane. The silicon is removed from under the membrane by micromachining to reduce the dielectric loss and the heat loss through the silicon. The thermocouples are more uniformly distributed along the heater using photolithographic technology than for MJTC's made by hand from wire. The temperature distribution is, therefore, more uniform along the heater, and the Thomson effect is reduced. Because of this construction, the ac-dc differences of the thin-film MJTCs as current and voltage converters are very small, usually only a few ppm at 1 kHz.

II. GEOMETRIC DESIGN

The new integrated, thin-film micropotentiometers contain all the essential electrical elements of the conventional micropotentiometers. Planar, thin-film MJTC's [7] and one or more thin-film output resistors have been designed and fabricated on the same chip to achieve high thermal efficiency and optimum electrical performance (see Figs. 2 and 3). The heaters are 1.6 mm long and are fabricated of a quaternary alloy. The 40 thermocouples, heaters, and output resistors are each no more than a few thousand Angstroms thick. The output resistors are connected directly to one pad of the heater. Custom packages have been designed and fabricated to provide long-term stability, small distributed capacitance and inductance, and minimum skin effect through the use of all nonmagnetic materials [7]. The new converters routinely undergo commercial cleaning, mounting, wire bonding, and sealing, thus demonstrating that they are not too delicate to withstand these necessary operations. Current is supplied to the integrated micropotentiometers through bonded wires at the input edge of the chip. The output signals are collected in a similar manner at the output resistors.

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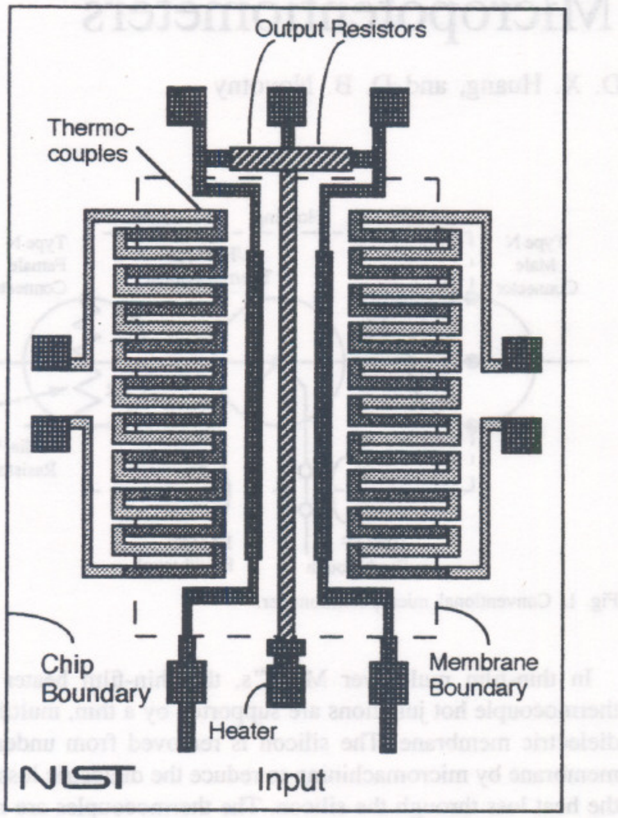

Fig. 2. Schematic diagram of single-range, integrated thin-film micropotentiometer. The membrane size is approximately 1.6 × 1.6 mm. The vertical scale has been expanded to show detail.

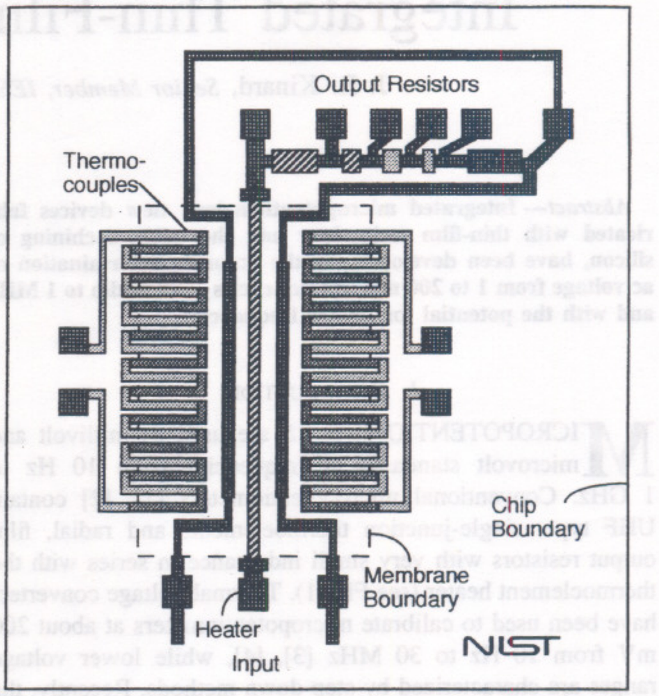

Fig. 3. Schematic diagram of multirange, integrated thin-film micropotentiometer. The membrane size is approximately 1.6 × 1.6 mm. The vertical scale has been expanded to show detail.

In these new structures, the distance between the output resistor and the thermal converter, in this case a multilayer, thin-film MJTC, is reduced more than an order of magnitude compared to conventional micropotentiometers. This reduces the standing wave error in the current measurement which is proportional to the square of the frequency and the distance between the center of the heater and the output resistors. The ac-dc difference arising from this error can be larger than 1500 ppm at 1 MHz for some traditional, commercial multirange micropotentiometers. The skin effect cannot be neglected in the traditional micropotentiometer; however, the MJTC heaters and thin-film output resistors are so thin in the new structures that the thicknesses of the metal films are usually less than the skin depth up to 100 MHz. The skin effect contribution from them can, therefore, be neglected. Skin effect remains a factor in the connections and mountings.

Several different types of integrated, thin-film micropotentiometers have been made. Most of the new micropotentiometers were single-range versions with a 5 mA MJTC combined with either a 20 Ω, 2 Ω, or 0.2 Ω resistor. Others were multirange with as many as five voltage ranges from 1 mV to 200 mV. Several other variations in the structural details have been investigated including positioning the output resistor on the membrane or over the silicon, different types of MJTCs, and novel current return paths. Geometries of the MJTC and output resistor have been designed to minimize Thomson and Peltier effects, dielectric losses, and distributed inductances and capacitances, where practical.

III. Measurement Results

The micropotentiometer with single-range output resistors can be connected as a micropotentiometer, as an MJTC thermal voltage converter (TVC), or as an MJTC thermal current converter (TCC). This flexibility broadens the range of useful applications for this device. If the micropotentiometer is connected as a TVC or TCC, the output resistor can be shorted at the output connector or not shorted. The effect on the dc reversal error is usually less than 1 ppm because the heat produced by the output resistor on the silicon is conducted away quickly since the thermal conductivity of the silicon is higher than for many metals. This indicates that the Peltier effect at the heater pads could be almost eliminated by locating the pads over the silicon frame. The ac-dc difference up to 1 MHz of the micropotentiometer as a TCC with the output resistor shorted is sometimes lower than with the output resistor open, especially, when the output resistor value is relatively large.

The ac-dc differences of an integrated micropotentiometer when connected and used as a 1 V TVC, with the output resistor open, are smaller than with the resistor shorted externally, as shown in Table I. The inductance and skin effect of the thin-film output resistor are very small, while the external shorting adaptor increases the inductance and skin effect somewhat, therefore increasing the ac-dc difference at high frequencies.

When connected and used as a micropotentiometer, the device is sensitive to the mounting geometry inside the shielding box. There are current return paths on the thin-film membrane

TABLE I
EFFECT OF MULTIPLE CURRENT-RETURN PATHS ON ac-dc DIFFERENCES (ppm) OF 2 Ω, INTEGRATED MICROPOTENTIOMETER

Frequency (kHz)	2 Ω output resistor open	2 Ω output resistor shorted
20	0.6	1.5
50	6	9
100	10	16
200	16	37
500	42	92
1000	80	214

from the output resistors to the ground connections. If the ratios of the ac impedance to dc resistance are approximately symmetric for these paths, the ac-dc differences will be small. If the output resistors are connected directly to a nonisolated output connector, i.e. one which is electrically joined to the shielding box, then return current paths will exist both through the metal box and along the return paths on the chip membrane. Since the ratios of the ac impedance to dc resistance are so different, the ac-dc differences will be relatively large. The ac output voltage is a function of the ac reactance of the output resistor and its various lead geometries as well as the accuracy of the ac current flowing through the resistor.

Tables II and III show the measurement results. Commercial micropotentiometers characterized at NIST were used as reference standards, and a commercial amplifier-aided TVC was used as a transfer instrument. The resolution of the measurements on the micropotentiometers was limited by the stability of the amplifier. It ranged from a few ppm at full scale to several tens of ppm at 20% of full scale. The ac-dc differences of the thin-film, integrated micropotentiometers are generally a few ppm at audio frequency. This performance is close to the presently available calibration uncertainty. The RF-dc differences of the single-range, integrated micropotentiometers are usually several percent up to 100 MHz.

IV. CONCLUSIONS

These new integrated micropotentiometers combine high-performance, thin-film MJTC's with various thin-film, output resistor geometries on the same chip by means of a technology suitable for mass production. They are suitable as millivolt and microvolt standards of ac-dc difference and ac voltage for the calibration of ac calibrators, signal sources, and voltmeters up to 1 MHz with the potential for higher frequencies up to 100 MHz. In addition to these conventional micropotentiometer applications, they are usable as thermal current converters in the 5–10 mA range and as thermal voltage converters at about 1 V.

TABLE II
AC-DC DIFFERENCES (ppm) OF 20 Ω, INTEGRATED MICROPOTENTIOMETER

Frequency (kHz)	As μpot at 82 mV	As TVC at 1 V	As TCC at 5 mA
0.1	-13	+94	+4
0.4	--	+15	--
1	-21	+1	-4
20	-30	+5	+4
50	-49	+10	+7
100	-60	+21	+10
200	-76	+42	+8
500	-9	+132	-15
1000	+44	+323	-91

TABLE III
AC-DC DIFFERENCES (ppm) OF 2 Ω, INTEGRATED MICROPOTENTIOMETER

Frequency (kHz)	As μpot at 10 mV	As TVC at 1 V	As TCC at 5 mA
0.1	-1	+107	+5
1	+2	0	-2
20	+18	+1	0
50	+34	+2	+8
100	+42	+7	+26

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