Thermal Converters as AC-DC Transfer Standards for Current and Voltage Measurements at Audio Frequencies

Francis L. Hermach's paper [1] launched the field of ac-dc thermal transfer metrology, which forms the basis for ac voltage and current measurement and calibration throughout the world. It laid the foundation for the techniques of ac-dc transfer and provided the first theoretical basis for the thermal transfer structures used in all national measurement institutes (NMIs, i.e., counterpart organizations to NIST) today. Hermach was the first to realize the very large improvement in capability that is possible when electrothermic elements are used as ac-dc transfer devices instead of relying on absolute instruments as had been the practice previously. The impact of the paper was, therefore, nothing less than the creation of an area of electrical metrology that continues to provide the national and working standards on which the world's NMIs base their ac voltage and current calibrations.

Although the paper contains construction details and experimentally determined characteristics for new instrumentation developed at NBS, it also has over five pages of very detailed electrical, thermal, and thermoelectric modeling for the critical elements in the newly proposed thermal transfer standards. It contains the very first solution to the steady state temperature distribution in an ac-dc thermal transfer instrument and includes effects of Peltier and Thomson heating and low frequency error due to failure to average the applied signal.

This ground-breaking publication is the most cited work in the ac-dc thermal transfer field. It has been and continues to be cited by scientists and engineers in NMIs all over the world and is regularly mentioned for providing the basis of new calibration standards. Virtually every major NMI has a copy in its technical library. The paper is still disseminated routinely to metrologists who require a solid foundation in the field of thermal transfer measurements.

Hermach's paper made a major contribution by proposing and describing the use of electrothermic instruments as transfer devices, as well as clearly delineating the major physics elements limiting their performance, thus creating a whole new area of calibration standards.

AC voltages and currents in the frequency range from low audio to hundreds of megahertz are measured most accurately by comparison to dc standards using ac-dc thermal transfer instruments. AC-DC thermal transfer structures were first applied in the audio frequency range and later at radio frequencies [2] for difference measurements of voltage, current, and power. Hermach and the staff of the NBS Electricity Division produced important developments including the first description of coaxial transfer standards and the first transmission-line analysis of such structures [3].

In general, the rate of transformation of energy from electrical to thermal form in thermal converters is proportional to the root-mean-square (rms) values of current and voltage. The heater temperature is a function of the square of the heater current even if the constants in the defining equation that describes the underlying physics vary with temperature or time. Since the response of thermal converters is calibrated on direct current at the time of use, ac-dc transfers are possible with little decrease in accuracy from drift or external temperature influences.

Traditional thermal converters contain wire heaters or thin metal heater structures. The temperature of the heater is typically monitored with one or more thermocouples, also made of wire or thin metal film. The best-performing primary standards usually contain many thermocouples in an arrangement that minimizes ac-dc difference by reducing both heater temperature and thermal gradients. Current research at NIST includes two areas directed at new thermal converters suitable for both primary and working standards.

Multi-junction thermal converters (MJTCs) are used in very high-accuracy ac-dc difference metrology because they have very small ac-dc differences, follow the rms law of excitation, and produce high output emfs. MJTCs traditionally have been fabricated from wire heater resistors and thermocouples. The project to develop thin-film MJTCs (FMJTCs) involves the use of micro-machining of silicon and photo-lithography on thin films to produce high-performance thermal transfer standards. Multilayer FMJTCs have been designed, fabricated, and tested at NIST by J. R. Kinard, D. B. Novotny, and D. X. Huang, and new improved converters are under development [4].

The basic elements of the devices are a thin-film heater on a thin dielectric membrane, a silicon frame surrounding and supporting the structure, and thin-film thermocouples positioned with hot junctions near the heater and cold junctions over the silicon. Carefully selected materials in new thermal designs are required, along with very accurate dimensioning of the heater and thermocouples. The heater and thermocouples are sputter deposited and patterned with photolithography. Contributions to ac-dc difference from the Thomson effect and other effects are further reduced by the appropriate choice of heater alloy.

Integrated micropotentiometers are thermal transfer devices that contain FMJTCs and thin-film output resistors fabricated as an integrated structure on the same silicon chip. The figure shows an integrated micropotentiometer including the FMJTC structure. New versions of the FMJTCs and integrated micropotentiometers are under development that include new membrane materials and vacuum packaging, with the help of novel etching techniques such as front and back surface etching.

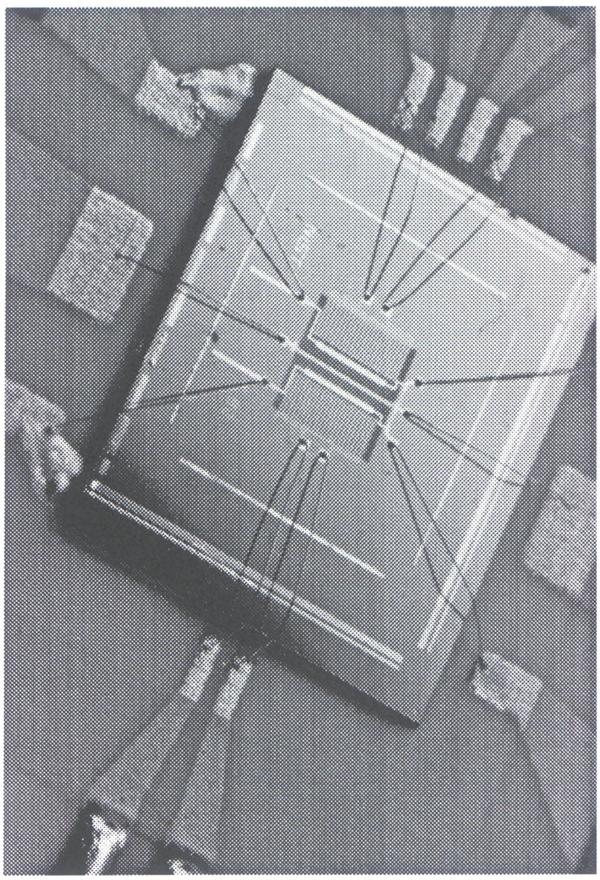

Fig. 1. Integrated micropotentiometer including the thin-film multijunction thermal converter (FMJTC) structure.

At audio frequency, thermal and thermoelectric effects ultimately limit the measurement uncertainty in conventional room-temperature thermal converters. Heater powers as high as a few tens of milliwatts and temperature differences as high as 100 K are common in some thermal converters. To reduce these effects and to achieve very high temperature sensitivity, a novel sensor employing a superconducting resistive-transition edge thermometer is being developed at NIST by C. D. Reintsema, E. N. Grossman, J. A. Koch, J. R. Kinard, and T. E. Lipe [5,6]. Since the new converter operates at temperatures below 10 K and is mounted on a platform with precise temperature control and very small temperature gradients, the thermal and thermoelectric errors are potentially quite small. Because of the very high temperature sensitivity of the superconducting transition, this converter also offers the possibility of direct thermal transfer measurements at very low signal levels.

This transfer standard consists of a signal heater, trim heater, and temperature sensor all mounted on a temperature-stabilized platform. The sensor resistance is measured by an ac resistance bridge, and the temperature of the assembly is held constant by the closed loop application of power to the trim heater. A NbTa thin-film meander line is used as the thermal sensor, and it is thermally biased to operate within its superconducting-resistive transition region. The signal heater in the prototype device is a 7 Ω thin-film meander line and the trim heater is a 450 Ω PdAu thin-film meander line, both adjacent to the detector on the silicon substrate. To ensure temperature stability, the entire converter assembly is mounted on a second platform controlled at a slightly lower temperature. This intermediate stage is thermally isolated, and controlled by a second ac resistance bridge using another transition edge sensor and heater.

Using this new cryogenic converter, measurements have been made at signal power levels of a microwatt, which is around 1000 times lower than is possible with room-temperature converters. Characterization using a fast-reversed-dc source has shown that the thermoelectric errors are presently in the 1 μV/V to 2 μV/V range. These early results are encouraging, but considerable improvement both in the resistance bridge performance and in the input transmission line will be necessary for this new device to be a candidate for consideration as a primary standard.

Prepared by J. R. Kinard, Jr., N. B. Belecki, and J. F. Mayo-Wells, based on excerpts from the paper The Ampere and Electrical Units [7], *authored by members of the Electricity Division.*

Bibliography

[1] Francis L. Hermach, Thermal Converters as AC-DC Transfer Standards for Current and Voltage Measurements at Audio Frequencies, *J. Res. Natl. Bur. Stand.* **48**, 121-138 (1952).

[2] F. L. Hermach and E. S. Williams, Thermal voltage converters for accurate voltage measurements to 30 megacycles per second, *Trans. Am. Inst. Electr. Eng., Part 1* **79**, 200-206 (1960).

[3] Joseph R. Kinard, Thomas E. Lipe, Clifton B. Childers, and Svetlana Avramov-Zamurovic, Comparison of high voltage thermal converter scaling to a binary inductive voltage divider, in *1998 Conference on Precision Electromagnetic Measurements: Digest,* Institute of Electrical and Electronics Engineers, New York (1998) pp. 381-382.

[4] J. R. Kinard, D. X. Huang, and D. B. Novotny, Performance of multilayer thin-film multijunction thermal converters, *IEEE Trans. Instrum. Meas.* **44**, 383-386 (1995).

[5] Carl D. Reintsema, Erich N. Grossman, Jonathan A. Koch, Joseph R. Kinard, and Thomas E. Lipe, AC-DC transfer at cryogenic temperatures using a superconducting resistive transition-edge temperature sensor, in *IMTC Proceedings: IMTC '97, IEEE Instrumentation and Measurement Conference: Sensing, Processing, Networking, Vol. 1,* Institute of Electrical and Electronics Engineers, New York (1997) pp. 726-730.

[6] Carl D. Reintsema, Joseph R. Kinard, Thomas E. Lipe, Jonathan A. Koch, and Erich N. Grossman, Thermal transfer measurements at microwatt power levels, in *1998 Conference on Precision Electromagnetic Measurements: Digest,* Institute for Electrical and Electronics Engineers, New York (1998) pp. 171-172.

[7] R. E. Elmquist, M. E. Cage, Y-H. Tang, A-M. Jeffery, J. R. Kinard, R. F. Dziuba, N. M. Oldham, and E. R. Williams, The Ampere and Electrical Units, *J. Res. Natl. Inst. Stand. Technol.,* January-February (2001).