active layer. Besides traps 1 and 2, a third trap ($\Delta E_3 = 0.47$ eV), interpreted as the *DX* center related to Si, was also found.[10] It should be stressed that in the case of Si, with its well-known amphoteric behavior, the concentration of the *DX* centers related to Si was 10^{-3} times the free-carrier concentration, which is two orders of magnitude lower than the concentration of trap 2 in this sample.

Concluding, the results presented show that the trap with thermal activation energy equal to 0.33 eV can be interpreted in the multivalley conduction-band structure model as the *DX* center related to Sn and associated with the *L* minimum in the range of Al content studied. At the same time that trap 2 goes through a maximum as a function on the Al content, a continuous increase of trap 1 population is observed. In this context, it can be suggested, that the trap, with thermal activation energy of $\Delta E_1 \sim 0.21$ eV, is attached to the *X* minimum. The question needs, however, to be further investigated before any firm conclusions in the matter are reached.

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Use of high-T_c superconductors for the determination of absolute thermoelectric power

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The use of the recently discovered high-T_c superconductors for purposes of precision determination of the absolute thermoelectric power is illustrated on commercially available wires of copper and Nb-Ti. High-T_c superconductors offer a wide range of temperatures where precision metrology can be carried out, and their unusually steep upper critical field allows for an accurate determination of the effect of magnetic field on the thermopower of test leads.

Measurements of the thermoelectric power are among the most frequently performed transport investigations. The interest stems not only from the fact that such studies provide fundamental parameters concerning the carrier spectrum,[1] but that they are also directly relevant to technologically important applications such as thermoelectric energy conversion devices[2,3] and thermocouple temperature sensors.[4]

Experimentally, it is difficult to determine the thermoelectric power of a single element. Consequently, a typical experimental setup consists of a thermoelectric circuit formed from a material under investigation and a reference material, the resultant thermopower being the difference between the thermopowers of the two constituents. In order to make the measurements meaningful, particularly in situations where the specimen has a small thermopower, it is essential to know accurately the absolute thermopower of the reference material.

It was recognized a long time ago that for work below room temperature, Pb is especially useful as a reference material because of its relatively small thermopower and substantial insensitivity to trace amounts of impurity elements. The first thermopower scale based on Pb was assembled by Christian *et al.*[5] in 1958, and as one of their inputs, they used the data of Borelius *et al.*[6] from the early 1930s on the Thompson coefficient of Pb. A great majority of the existing thermopower data, including extensive investigations in the particularly busy period of the 1960s, use this scale as a reference. In 1977 Roberts[7] determined the absolute thermopower of lead by direct measurement of its Thompson heat and found significant errors in the original thermoelectric scale amounting to as much as 0.3 μV/K above 20 K. Errors of this magnitude are, of course, inevitably present in all the thermopower data published prior to 1977 and are often propagated even into more recent tabular compilations.

While Pb itself would seem to be a good choice for the Seebeck probe, in practice its direct use is limited by the difficulties of making sufficiently thin wires. Since the thermopower is frequently studied simultaneously with the thermal conductivity, heat loss along the relatively thick Pb leads presents a serious drawback. Experimental conditions are made even more difficult when one desires to apply an external magnetic field. In that case a rather large magnetothermopower[8] of Pb (particularly below 25 K) compli-

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cates the data reduction. For these reasons the Seebeck probes are usually chosen from materials that can be drawn into very thin wires such as Cu, Nb-Ti, Chromel, Constantan, etc., in spite of the latter three having typically an order of magnitude higher thermopower than Pb itself. Even if the thermopower of these selected wires is properly established, the uncertainties in their magnetothermopower remain.[9,10]

An ideal reference material should have zero absolute thermopower and be immune to external stimuli such as magnetic field. These conditions are substantially satisfied by superconductors. Until very recently, the temperature range over which the intrinsically zero thermopower of a superconductor could be utilized was limited to about 18 K, the transition temperature of Nb_3Sn tapes or composite wires. With the discovery of high-T_c superconductors based on the $YBa_2Cu_3O_7$ phase,[11] one has available an ideal reference material with zero thermopower up to about 92 K. Furthermore, because of its steep upper critical field $(dH_{c2}/dT \simeq -1.3\ \mathrm{T/K})$, one has a wide range of temperatures over which the typical magnetic field available in the laboratory has no effect on the (zero) thermopower. While this superconducting compound is not yet available in the form of a thin wire to be used directly as the Seebeck probe, its bulk form provides a very convenient material for a rapid and precise determination of the absolute thermopower of any section of wire arranged in a thermoelectric circuit with this high-T_c superconductor.

In this communication I wish to illustrate the usefulness of high-T_c superconductors for purposes of thermopower calibration on two specific materials, copper and Nb-Ti wires. The low-temperature thermoelectric properties of copper are strongly dependent on the amount of residual impurity (particularly iron, resulting in the pronounced Kondo anomaly), heat treatment, and the drawing process, which all make the universal tabulation of its thermopower below the liquid-nitrogen temperature rather impractical, but copper is, nevertheless, the laboratory's most frequently used connecting wire, and it may be desirable to know the thermopower of a particular spool on hand. In our case the material is a 0.071-mm-diam KL-Lötbar VJ type copper manufactured by Leonische Drahtwerke AG in Nurnberg. The second material is a representative of a class of Nb-Ti-based wires which are extremely useful as test leads in low-temperature applications. It is appealing not only for its relatively high superconducting transition temperature of about 10 K, but also because it is readily available in a metallurgically bonded copper-nickel matrix that can be easily soldered and has a very small thermal conductivity. The spool which we use extensively in our laboratories is a Vacryflux 5001, type SKN1 wire of 0.05 mm diameter, insulated with a polyester-Imide-based lacquer and manufactured by Vacuumschmelze in Hanau, Germany.

Thermopower calibration was carried out in a helium cryostat equipped with a 7-T superconducting solenoid. Wires under test were attached to a bar-shaped sample of $YBa_2Cu_3O_7$ with the aid of a silver epoxy. One end of the superconductor was fastened to a slotted cold tip of the cryostat with Stycast, the other end being provided with a metal film resistor serving as a heater. The temperature gradient across the superconducting bar was determined with a pair of calibrated glassy-carbon thermometers and a differential Au/Fe-Chromel thermocouple attached opposite to the points where the Seebeck probes were fastened. We estimate about 5% uncertainty resulting from a possible misalignment between the thermometers and Seebeck probe contacts. Thermoelectric signals were detected on a Keithley 181 Nanovoltmeter with a resolution better than 10 nV.

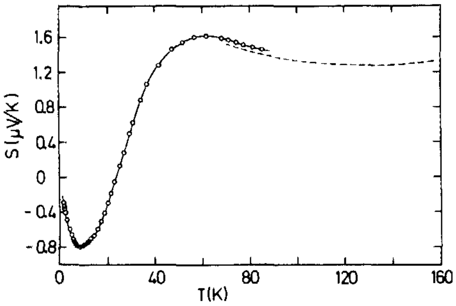

FIG. 1. Temperature dependence of the thermopower of copper. Dashed line indicates the data of Ref. 12 adjusted according to the thermoelectric scale of Pb given in Ref. 7.

The data for the two types of wires are shown in Figs. 1 and 2. In the case of copper we note a Kondo-type anomaly resulting in a deep minimum near 8 K followed by a broader phonon-drag contribution peaking around 60 K. Our copper data join quite well (a jump of only about 0.04 μV/K) the high-temperature thermopower of copper determined by Crisp, Henry, and Schroeder,[12] provided that the latter is corrected in the spirit of the thermoelectric scale of Roberts. The thermopower of our Nb-Ti wire is less eventful. Following a jump at the superconducting transition temperature of about − 1.3 μV/K, the thermopower increases in magnitude with increasing temperature and reaches − 8 μV/K at 90 K. I am unaware of any published data on the thermopower of Nb-Ti wires to provide a comparison. It is clear, however, that at higher temperatures the thermopower of this type of wire is substantial and, if unaccounted for, would cause serious errors in the measurements where this wire is used as the Seebeck probe.

The effect of magnetic field on the thermopower is shown in Fig. 3. The data for copper were taken at 4.4 K and that for Nb-Ti at a temperature of 10.3 K, just above its superconducting transition temperature. While the thermopower of Nb-Ti is relatively little affected by the magnetic field (only about 23% increase at 7 T) and shows saturation

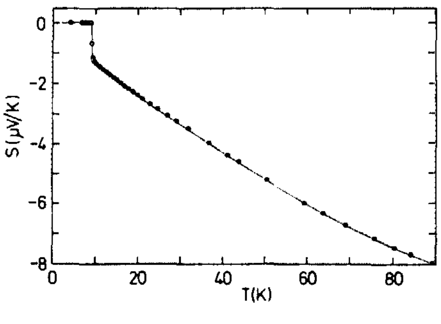

FIG. 2. Thermopower of our Nb-Ti wire.

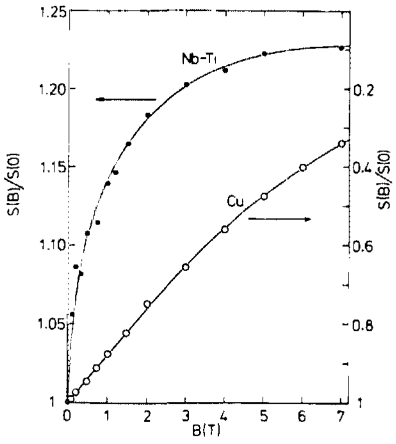

FIG. 3. Magnetic field dependence of the thermopower of Cu and Nb-Ti wires. The data for Cu are taken at 4.4 K, while that for Nb-Ti at 10.3 K.

in high fields, in the case of copper the effect is far more dramatic, yielding a change in the thermopower (field reduces magnitude of the negative thermopower) by a factor of 3 at 7 T. This large magnetic field effect persists to higher temperatures, and at 32 K and 7 T it amounts to a 3.5 times increase of the (now positive) thermopower over its zero-field value. Such large magnetothermopowers underscore the difficulties of using copper for low-temperature thermopower/magnetothermopower probes without a proper calibration of the wire.

In conclusion, I have shown that the recently discovered high-T_c superconductors based on the oxygen-deficient perovskites and, in particular, the 92-K $YBa_2Cu_3O_7$ phase offer an ideal medium for the determination of the absolute thermopower of any wire intended for use as thermopower probes. The advantages are not only in the exceptionally high superconducting transition temperature, providing a wide range of temperatures for the calibration purposes, but also in the extremely high critical fields which allow for the precise determination of the effect of magnetic field on the thermopower. Latest reports on superconductivity in the 150 K (Ref. 13) range coupled with an intensive search worldwide, promise to revolutionize the field of precision metrology even further.

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Ensemble Monte Carlo simulations of femtosecond thermalization of low-energy photoexcited electrons in GaAs quantum wells

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We present results of ensemble Monte Carlo simulations of the room-temperature relaxation of nonthermal photoexcited electrons in GaAs quantum-well structures. Electrons are excited at a mean energy of 20 meV above the band edge, similar to the experiments of Knox *et al.* [Phys. Rev. Lett. **56**, 1191 (1986)] and Oudar *et al.* [Phys. Rev. Lett. **55**, 2075 (1985)]. Since this energy is less than the optical-phonon emission threshold, energy relaxation occurs primarily via carrier-carrier scatterings. We find that the excited electrons thermalize with the background electrons within 200 fs, in agreement with experiment.

The energy relaxation of photoexcited electrons in semiconductors has recently been studied experimentally with the use of sophisticated ultrafast laser-probe techniques.[1-6] In the past several years much of this work has concentrated on the study of electrons excited well above the bottom of the conduction band edge.[3-6] Consequently, longitudinal-optical phonon scattering has been the principal agent of energy

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