

## Frequency Dependence of Magnetocrystalline Anisotropy

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IT is well known that the magnetocrystalline anisotropy constant  $K_1$  can be determined both by static measurement of the torque on a single crystal placed in a strong magnetic field, and by measurement of the magnetic field for resonance at microwave frequencies. In experiments on several specimens of nickel-iron ferrites it was apparent that the same value of  $K_1$  was not obtained by the two methods. In order to determine whether the difference was due to chemical composition or to a true frequency dependence, measurements were made by both methods on specimens cut from the same single crystal. The crystal was obtained from Dr. G. W. Clark of Linde Air Products Company; chemical analysis for Ni and Fe indicate that it has the composition  $\text{Ni}_{0.76}\text{Fe}_{2.16}\text{O}_4$ . The simplest formula preserving these proportions is  $(\text{NiO})_{0.70}\text{Fe}_2\text{O}_3$ , which calls for metal ion vacancies in the lattice but no  $\text{Fe}^{++}$  ions. The electrical resistivity of this material at room temperature, however, is  $\rho=1$  ohm-cm, and we believe that this low value of resistivity indicates at least the temporary existence of  $\text{Fe}^{++}$  ions.

Our results, given in Table I, show that the difference

TABLE I. Magnetic anisotropy constant  $K_1$  in ergs/cm<sup>3</sup>, and anisotropy field  $2K_1/M_s$  in oersteds, as dependent on frequency and temperature.

Quantity	Temperature	$\text{Ni}_{0.8}\text{Fe}_{2.2}\text{O}_4$		$\text{Mn}_{1.6}\text{Fe}_{1.4}\text{O}_4$	
		Static	Microwave	Static	Microwave
$K_1$	20°C	$-39 \times 10^3$	$-43 \times 10^3$	$-34 \times 10^3$	$-33 \times 10^3$
$K_1$	-196°C	$-42 \times 10^3$	$-74 \times 10^3$	$-240 \times 10^3$	$-233 \times 10^3$
$2K_1/M_s$	20°C	-260	-280	-180	-175
$2K_1/M_s$	-196°C	-260	-468	-840	-812

in  $K_1$  is slight at room temperature but marked at  $-196^\circ\text{C}$ . This difference is the first time to our knowledge that frequency dependence has been observed in a magnetocrystalline anisotropy constant.

The conclusion that  $\text{Fe}^{++}$  ions are present leads us to believe that this variation of  $K_1$  with frequency confirms the interpretation which some of us have given<sup>1</sup> to relaxation phenomena observed in other crystals where  $\text{Fe}^{++}$  ions were certainly present. This interpretation starts with the assumption that there are  $\text{Fe}^{++}$  and  $\text{Fe}^{+++}$  ions in the crystal on which the valence electrons rearrange easily with a short time constant as suggested some time ago by Verwey.<sup>2</sup> It is then suggested that these electronic rearrangements occur as the magnetization changes direction, and affect the magnetocrystalline anisotropy constant, so that the value of  $K_1$  will differ depending on whether it is measured at an angular frequency above or below the reciprocal of the

time constant for the electronic rearrangement. The microwave measurements indicate that the reciprocal of this time constant corresponds to 24 000 Mc/sec at about  $160^\circ\text{K}$ .

A similar comparison of static and microwave measurements of magnetocrystalline anisotropy on a single crystal of manganese ferrite of composition  $\text{Mn}_{0.98}\text{Fe}_{1.86}\text{O}_4$ , was made using our static value and the dynamic values deduced by S. Geschwind and J. F. Dillon, Jr. from their microwave measurements at  $20^\circ$  and  $-196^\circ\text{C}$ , at frequencies of 9300 and 48 000 Mc/sec. These values, also given in Table I, show that  $K_1$  is practically independent of frequency in this material. This indicates that electrons are not free to move so easily from one atom to another in this material as compared with the nickel-iron ferrite.

We are indebted to S. Geschwind and J. F. Dillon, Jr., for permission to quote their results before publication, and to F. J. Morin for the measurement of resistivity.

<sup>1</sup> Galt, Yager, and Merritt, *Phys. Rev.* **93**, 1119 (1954); J. K. Galt, *Bell System Tech. J.* **33**, 1023 (1954).

<sup>2</sup> E. J. W. Verwey, *Nature* **144**, 327 (1939).

## Emission Spectroscopy at Liquid Helium Temperature\*

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A KOVAR and glass hollow-cathode discharge tube has been operated immersed in liquid helium, to study the emission spectrum of helium. The spectrum was recorded directly from an RCA 1P21 photomultiplier, with a Perot-Fabry interferometer and a 21-foot stigmatically mounted concave grating swept in synchronism.<sup>1,2</sup> The grating was swept by moving the exit slit, and the Perot-Fabry by varying the interplate gas pressure linearly with time. The entrance and exit slits were curved to concentrate the light into a single interference fringe. Details will be published after further work in improving the signal-to-noise ratio.

The line  $\sigma=21\,335$  K ( $\lambda=4686$  Å) of He II was observed, and the Doppler broadening was found to be sensibly reduced from the amount observed with liquid-air cooling. The splitting arising from the radiation shift<sup>3</sup> was clearly shown. In particular, the  $3s_3-4p_3$  and  $3p_3-4s_3$  pair was almost completely resolved and the  $3s_3-4p_3$  and  $3p_3-4d_3$  pair was partly resolved.

It was found that a discharge could be not only maintained at this low temperature, but easily started as well. In all, about three liters of liquid helium were consumed in 25 minutes' operation of the discharge. The current averaged 30 milliamperes and the potential difference 250 volts.

It is concluded that liquid helium can certainly be used to advantage to cool a helium discharge in cases where Doppler broadening presents a serious problem at liquid air or even liquid hydrogen temperatures, and that no serious experimental difficulties are experienced.

It is expected that by using helium as a carrier gas, the spectra of other elements can be obtained at liquid helium temperature as readily as at liquid air temperature.

This work was suggested by Professor J. E. Mack. The liquid helium was very kindly supplied by Professor J. R. Dillinger and his group. An especially sensitive photomultiplier was lent by Professor A. D. Code of the department of astronomy. The Perot-Fabry plates were multilayer-coated for  $\sigma$  21 335 at Bellevue laboratory through the courtesy of Professor P. Jacquinot, with whom I have had the privilege of discussing high-resolution techniques.

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<sup>1</sup> J. G. Hirschberg, Phys. Rev. **99**, 623(A) (1955).

<sup>2</sup> Since our initial use of the sweeping system our attention has been called to the suggestion of a somewhat analogous system by J. H. Jaffe, Nature **168**, 381 (1951).

<sup>3</sup> J. E. Mack and N. Austern, Phys. Rev. **72**, 972 (1947).

## Nature of the Water-Vapor-Induced Excess Current on Grown Germanium $p$ - $n$ Junctions

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IT is well known that water vapor can induce large excess currents on germanium  $p$ - $n$  junctions biased in the reverse direction. What is not well understood or agreed upon at present is the nature of the water-vapor-induced currents. In general, the excess current might be either ionic or electronic or possibly a combination of the two. Law<sup>1,2</sup> has presented evidence in favor of the ionic interpretation, while Christensen<sup>3</sup> and McWhorter and Kingston<sup>4</sup> have presented data which seem to favor an electronic interpretation. Electronic currents are associated with the presence of an electron-conducting layer or "channel" on the  $p$ -type germanium.

In the present work, a new criterion has been used to determine the nature of the water-vapor-induced current. This criterion involves comparison of two curves, namely, (1) the water-vapor-induced excess current-voltage curve and (2) a field-induced excess current-voltage curve. Such a comparison is shown in Fig. 1 and described below. For the field-induced channel, a positive electric field applied perpendicular to the surface attracts electrons to the surface inducing an electron conducting layer as shown in Fig. 2. The field-

induced experiment is carried out in air in the absence of water vapor, and control of the channel conductance is achieved by means of the external inducing field. The present field experiment is carried out at 207°K because such a dc field-induced conducting layer is stable only at low temperatures.<sup>5</sup> It is sometimes necessary to use even lower temperatures to stabilize the channel. In such an experiment, the possibility of ionic conduction through a thin surface film of water does not exist and it can then be concluded that the excess current flowing across the junction is wholly electronic in nature. If the water-vapor-induced excess current-voltage curve and the field-induced excess current-voltage curve are identical in shape as shown in Fig. 1, we shall conclude that the two mechanisms are likewise identical and hence that the water-vapor-induced current is electronic rather than ionic.

The results shown in Fig. 1 were obtained on a grown germanium  $p$ - $n$  junction having the following characteristics: approximate  $p$ -type resistivity 10 ohm-cm,

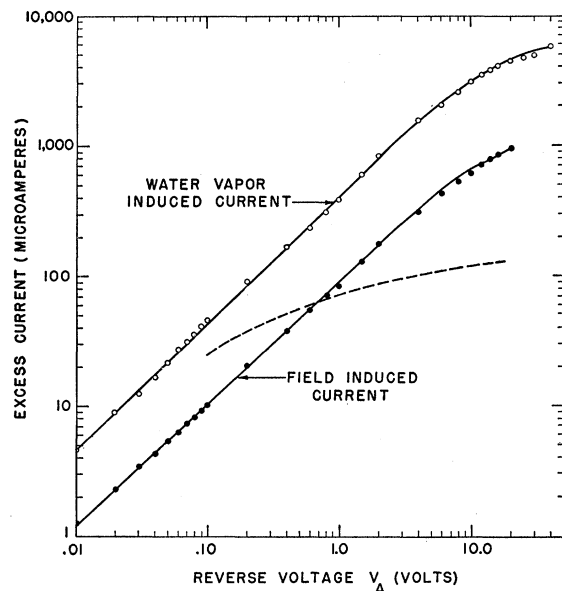


FIG. 1. Water-vapor-induced and field-induced excess current on the same germanium  $p$ - $n$  junction. Water vapor pressure corresponds to about 100% relative humidity. Field-inducing voltage has been chosen so that field-induced current is four times smaller than water-induced current. Dashed line shows current-voltage dependence expected from simple channel theory.

$n$ -type resistivity 1 ohm-cm, and junction circumference 1 cm. This is a particularly interesting case in which the water-vapor-induced excess current-voltage curve is not described by simple channel theory<sup>4</sup> which provides a current-voltage curve with shape shown by the dashed line. The measured excess current rises much more steeply with increasing voltage than predicted by simple channel theory. Nevertheless, the water-vapor-induced current in this case is electronic rather than