Direct Current Electroluminescence at Low Voltages

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Electroluminescence due to dc excitation occurs in activated ZnS films at 2.0 volts. Since in the dc case no ambiguity is introduced by possible transient potential differences within the phosphor layer, these experiments show that electroluminescence can occur at applied voltages corresponding to about half the band gap (3.8 electron volts) of the ZnS phosphor. The acceleration-collision theory of electroluminescence is thus ruled out at low voltage, and since no appreciable difference is found to be characteristic of the electroluminescence at low voltages, the acceleration-collision mechanism may not be important in any voltage range.

ELECTROLUMINESCENCE at very low voltages is of interest since it may indicate the nature of the basic electronic processes involved, or at least rule out some possibilities. A previous note[1] described observations of ac electroluminescence at voltages as low as 1.5 volts rms in activated ZnS films; this voltage corresponds to a peak voltage of 2.2 volts. As already pointed out,[1] in the ac case there is a possibility of space charge buildup with a relaxation time too long to allow complete decay every cycle; therefore it is possible, although unlikely, that the total minimum potential difference was 4.4 volts and that electrons could have been accelerated to energies greater than that equivalent to the band gap (3.8 electron volts) of the zinc sulfide.

More recent measurements of dc electroluminescence in similar films show that electroluminescence occurs at direct voltages at least as low as 2.0 volts, again corresponding to electron energies less than the band gap and less than the mean energy of the photons emitted. In the dc case, moreover, the possibility of transient potential differences greater than the applied voltage is eliminated.

Thin phosphor films[2] of ZnS:Cu, Mn, Cl about one micron in thickness were measured by the procedure reported previously[1] except for the use of a Regatron dc supply and Southwestern Industrial Electronics model R-1 dc voltmeter calibrated against a standard mercury cell. In Fig. 1 the low-voltage dc electroluminescence emission in foot-lamberts is plotted logarithmically against $V^{-\frac{1}{2}}$, where V is the applied direct voltage. The lowest plotted point corresponds to two volts, and there is no indication of a threshold voltage. The emission of these films consists predominantly of the yellow manganese emission near 2.1 electron volts with some blue emission near 2.7 electron volts, and the detector (RCA 6217 photomultiplier) cuts off near 1.8 electron volts.

The present results with dc excitation show in an even less equivocal manner that electroluminescence can be produced by applied voltages no greater than the equivalent mean photon energy of the resulting emission, and far less than the band gap of the base material or the optical excitation energy (2.8 electron volts) required. Thus the acceleration-collision[3,4] theory of electroluminescence is ruled out[5] at these low voltages; since the emission at low voltages seems not to be characteristically different from that at higher voltages, the acceleration-collision mechanism may not be important in any voltage range. If electroluminescence depends instead primarily on carrier injection, for example, trapping processes (of electrons or holes or both) can still be important, as is thought to be true particularly in the ac case. If electroluminescence depends on free electron temperature,[6,7] again no change

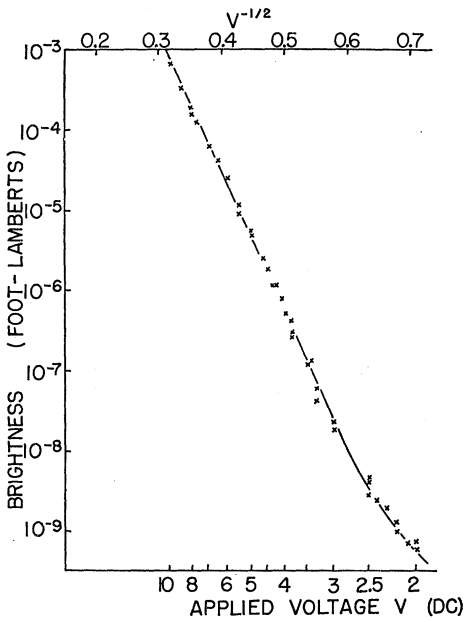

FIG. 1. The low-voltage dependence of dc electroluminescence emission from a thin film of ZnS:Cu, Mn, Cl.

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[3] D. Curie, J. phys. radium **13**, 317 (1952).
[4] W. W. Piper and F. E. Williams, Phys. Rev. **87**, 151 (1952).
[5] The same conclusion is reached, from quite different experiments, by I. T. Steinberger, V. Bar, and E. Alexander who kindly supplied a preprint of a paper which was read at the Torino meeting on Color Centers and Crystal Luminescence, September 7–11, 1960 (to be published).
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[7] E. Nagy, J. phys. radium **17**, 773 (1956); Acta Phys. Acad. Sci. Hung. **6**, 153 (1956).

in the general picture of the process seems required except that the necessity for a threshold in the applied voltage is eliminated.

Electroluminescence with dc excitation of similar films has led to brightnesses of six hundred foot-lamberts, with efficiency rapidly increasing with brightness or current. These additional results, together with response times, transient, and polarity effects, will be described elsewhere.

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Ferromagnetic Resonance Linewidth in Cobalt-Substituted Ferrites*

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The effect of small concentrations of substitutional ions on the ferromagnetic resonance linewidth of a host ferrite is calculated. The resonance linewidth arises from magnon scattering induced by the variation from ion-to-ion of the spin-orbit interaction. This interaction is uniquely large for cobalt ions because of the orbital degeneracy of the ground state of the ion in a trigonally-symmetric crystalline field. The resultant contribution to the linewidth is found to be isotropic and of the order of 20–30 oersteds for each percent of cobalt in normal (i.e., noninverse) ferrites or in ferrous ferrite. In other ferrites the effect is diminished by the lifting of the ground-state orbital degeneracy at some of the cobalt sites; this diminution is calculated as a function of the degree of inversion.

I. INTRODUCTION

IN typical ferrites, containing any of a large number of substitutional ions, the intrinsic ferromagnetic resonance linewidths are of the order of 10 oersteds. However, the cobalt ion is unique in that even small admixtures of cobalt increase the linewidth drastically.

A contribution to the linewidth in typical ferrites (without cobalt) has been calculated by Callen and Pittelli[1] on the basis of magnon scattering induced by the random variations from ion to ion of the spin-orbit and intra-atomic spin-spin coupling parameters. The resulting linewidth contribution is anisotropic, and is of the observed order of magnitude.[2]

We consider specifically the contribution of small concentrations of cobalt ions to the linewidth. The effect of the spin-orbit coupling is enhanced in this ion because it has a degenerate orbital ground state when situated in a crystalline field of trigonal symmetry. This leads to three important differences in our results: (1) The linewidth contribution of a cobalt ion is considerably larger than that of a typical (nondegenerate) ion. (2) The dominant linewidth contribution of a cobalt ion is isotropic. (3) The linewidth contribution of a cobalt ion can be strongly influenced by the degree of inversion of the host ferrite, because of the destruction of the trigonal symmetry and lifting of the ground state degeneracy.

It is, of course, clear that variations from ion to ion of other parameters also lead to spin-wave scattering, and thence to linewidth. The strongest interaction at play is the exchange interaction, but because the exchange commutes with the total spin, variations of exchange cannot scatter magnons of zero wave number and hence cannot contribute to the linewidth. Another source of possible scattering is the variation in anisotropy. For cobalt ions the anisotropy is particularly large, of the order of 10^5 oersteds, again because of the degeneracy of the ground state, as shown by Slonczewski.[3] For one percent cobalt the mean square fluctuating anisotropy field is of the order of $0.01 \times (10^5)^2 = 10^8$ oersteds^2. However, Callen and Pittelli have shown that in the absence of short-range order it requires locally varying fields with mean square magnitudes of the order of 10^{10} oersteds^2 to produce a linewidth of 10 oersteds. Consequently, the linewidth resulting from variations in anisotropy field is negligible.

Another mechanism leading to magnon scattering in disordered ferrites is the variation from ion to ion of the magnitude of the spin. Callen and Pittelli did not calculate this effect because it is clearly isotropic and consequently is distinguishable from their anisotropic linewidth. However, as we shall see, the linewidth contribution of cobalt ions arising from spin-orbit coupling is also isotropic, and it therefore becomes

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[3] J. C. Slonczewski, Phys. Rev. **110**, 1341 (1958).