below the lithium fluoride cutoff at 11.7 eV.

*Research supported in part by U. S. Air Force Office of Scientific Research.

[1]A. M. Smith, thesis, University of Rochester, 1961 (unpublished).

[2]G. R. Huggetts, thesis, University of Rochester, 1963 (unpublished).

[3]G. Baldini, Phys. Rev. 128, 1562 (1962).

[4]National Research Council Committee on Solids, Imperfections in Nearly Perfect Crystals (John Wiley & Sons, Inc., New York, 1952), p. 246.

[5]M. H. Reilly, Bull. Am. Phys. Soc. 11, 415 (1966).

[6]D. Beaglehole, Phys. Rev. Letters 15, 551 (1965).

[7]J. C. Phillips, Phys. Rev. 136, A1714 (1964).

[8]C. E. Moore, Atomic Energy Levels, National Bureau of Standards Circular No. 467 (U. S. Goverment Printing Office, Washington, D. C., 1958), Vol. 3.

[9]G. Baldini, Phys. Rev. 137, A508 (1965).

NEW ELECTRON-TUNNELING MEASUREMENT OF THE ENERGY GAP IN LANTHANUM

J. J. Hauser
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 1 August 1966)

Edelstein and Toxen[1] recently reported electron-tunneling measurements of the energy gap of lanthanum with the result that $2\Delta_0/kT_c = 1.65$. On the other hand, using similar measurements, we have found a value of 3.2 for $2\Delta_0/kT_c$, which is in much closer agreement with the BCS theoretical value of 3.52. It is possible that the difference between these experimental results is due to a large extent to the method of preparation of the lanthanum films.

The tunnel diodes were prepared by evaporating a 0.25-mm-wide strip of aluminum approximately 1000 Å thick onto a sapphier substrate, oxidizing it, and depositing a cross strip 0.25 mm wide of lanthanum by getter evaporation. The getter-evaporation technique was very similar to the getter-sputtering technique previously described.[2] This technique consists in evaporating the lanthanum with a mask over the substrate inside a small liquid-nitrogen-cooled can, so as to getter the interstitial gases such as oxygen and nitrogen. Subsequently, the mask is removed and the film is deposited in a much purer atmosphere than that of the bell jar (in the 10^{-6}-mm range). As lanthanum is very easily contaminated, the best results were obtained by keeping the substrate table at 77°K and keeping the junction under liquid nitrogen until measured. Since the tungsten filament from which the lanthanum was evaporated was at 2000°C and approximately 3 cm from the table, the substrate temperature was undoubtedly much above 77°K.

As can be seen from Table I, this technique yields films which when thick enough (≃10 000 Å) have an appreciably better resistance ratio than those reported previously.[1] The higher resistance ratio of the films evaporated at higher temperatures is most probably due to grain growth. A further difference between the films described by Edelstein and Toxen[1] and those described in Table I is the higher transition temperature of the latter. This higher transition temperature (as high as 6.7°K) seems to

Table I. Physical properties of lanthanum films.

Sample	T_c (°K)	ρ(room temperature)/ρ(7°K)	Thickness (Å)	Temperature of substrate table (°K)
La-1	6.65	7.2	4775	77
La-3	6.2	8	10 000	300
La-5	6.35	14	18 450	900
La-6	6.74	16	8000	700
La-8	5.24	...	2680	77
Al-Al_2O_3-La No. 2	5.00	4	2500	77
Al-Al_2O_3-La No. 3	5.15	3.8	2000	77
Al-Al_2O_3-La No. 7	5.26	6.8	4000	77
Al-Al_2O_3-La No. 9	5.85	8.1	10 500	77

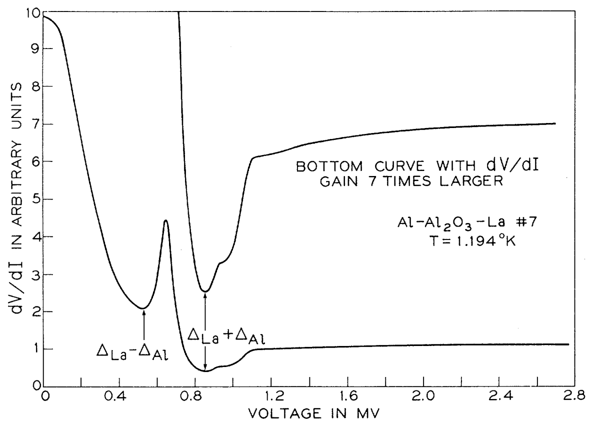

FIG. 1. dV/dI vs V for an Al-Al_2O_3-La junction; $d_{Al} \simeq 1000$ Å, $d_{La} = 4000$ Å.

be independent of the deposition temperature (within the range investigated) but depends on the thickness of the film and is lower the thinner the film. Films thinner than 1000 Å were not superconducting above 1.2°K.

The curves of dV/dI vs V were obtained using a standard modulation technique with an ac sensing signal of about 20 μV at a frequency of 10 000 cycles. Such a curve is shown in Fig. 1, and the value of $2\Delta_{Al}$ was obtained by summing the voltages corresponding to the two minima of dV/dI. These two minima correspond to the conductance peaks occurring at the difference and sum of the aluminum and lanthanum energy gaps. The shoulder at 0.95 mV in Fig. 1 is not reproducible from sample to sample and may be due to a multiple gap effect. A summary of the results from various tunnel junctions is shown in Table II. When the lanthanum films are fairly thin, the transition temperature as measured resistively (T_{cR}) agrees fairly well with that measured by the vanishing of the energy gap (this temperature $T_{c\Delta}$ is taken as the one where the curve dV/dI vs V becomes a straight line parallel to the voltage axis). The resistive transition temperature is always somewhat higher and becomes very much higher in thicker lanthanum films. The ratio $2\Delta_0/kT_{c\Delta}$ is approximately 3.2.

The fact that the energy gap is not higher in Al-Al_2O_3-La No. 9 with a resistive transition temperature of 5.85°K may be due to the fact that tunneling measures the portion of the film adjacent to the aluminum oxide. As mentioned previously, thin films have a lower transition temperature and, therefore, a lower energy gap. Consequently, tunneling which measures the first deposited layers of the film yields a low gap value, while the resistive measurement will of course measure the material with the highest transition temperature. Such an effect could be due to surface contamination with the substrate, or a difference in grain size or crystal structure in the first layers. It is quite possible that such an effect could have lead to the low energy-gap values previously reported for lanthanum.[1]

I would like to acknowledge discussions with H. C. Theuerer, who mentioned the possibility of getter evaporation. I would also like to thank D. D. Bacon for the evaporation of the films and W. H. Haemmerle for technical assistance.

[1]A. S. Edelstein and A. M. Toxen, Phys. Rev. Letters 17, 196 (1966).

[2]H. C. Theuerer and J. J. Hauser, Appl. Phys. 35, 554 (1964).

Table II. Experimental results for Al-Al_2O_3-La junctions.

Sample	$T_{c\Delta}$ ($\Delta = 0$)	T_{cR} ($R = 0$)	$2\Delta_0$ (mV)	$2\Delta_0/kT_{c\Delta}$
Al-Al_2O_3-La No. 2	5.0	5.0	1.375	3.18
Al-Al_2O_3-La No. 3	4.95	5.15	1.400	3.28
Al-Al_2O_3-La No. 7	4.9	5.26	1.380	3.26
Al-Al_2O_3-La No. 9	4.95	5.85	1.375	3.22