36, 432 (1964).

[2]V. Jaccarino, Magnetism, edited by G. T. Rado and H. Suhl (Academic Press, Inc., New York, 1964), Vol. II.

[3]This is the coupling parameter for a one-magnon interaction which is odd with respect to coordinate inversion.

[4]We have assumed $\vec{k} \parallel c$ axis. A calculation considering all spin-wave directions will be presented elsewhere.

[5]G. G. Low, A. Okazaki, R. W. H. Stevenson, and K. C. Turberfield, J. Appl. Phys. 35, 998 (1964).

[6]We used the value $H_A = 0.737$ cm^{-1} given by Charles Trapp and J. W. Stout, Phys. Rev. Letters 10, 157 (1963).

[7]F. Keffer, Phys. Rev. 87, 608 (1952).

[8]V. Jaccarino and R. G. Shulman, Phys. Rev. 107, 1196 (1957).

[9]J. W. Halley and I. Silvera, preceding Letter [Phys. Rev. Letters 15, 654 (1965)].

BALLISTIC MEAN FREE PATH MEASUREMENTS OF HOT ELECTRONS IN Au FILMS

C. R. Crowell and S. M. Sze

Bell Telephone Laboratories, Murray Hill, New Jersey

(Received 3 August 1965)

This letter describes a new experimental approach whereby the mean free path of excited electrons in metals can be directly obtained. Measurements have been made of the mean free path of 0.85-eV electrons in Au films deposited on Ge and Si substrates. The electrons are injected into Au films of varying thicknesses from a Si point contact. On the other side of the film, a constant fraction of the electrons which have not undergone a collision in the gold are collected over the Au-semiconductor Schottky barrier at the substrate-film interface. The size of this fraction is shown to be in good agreement with theoretical estimates, and the temperature-dependent portion of the mean free path is identified quantitatively with the electron-phonon conductivity mean free path. Transport of the above kind has been reported by Atalla and Kahng,[1] but has not been sufficiently stable or reproducible to be used in a quantitative fashion.

A cantilever-beam mechanism[2] (Fig. 1) capable of contact-separation adjustments as low as 10 Å has been used to contact metal films as thin as 100 Å without appreciable deformation of the films in order to make measurements of the incremental emitter-to-collector current-transfer ratio, α, as a function of film thickness. The cantilever beam and supporting yoke were constructed from a single piece of steel to provide a stable clamp for the beam. The yoke also served as a vibration-free support for the micromanipulators required to make the base contacts to the Au films and to make coarse adjustments of the contact position. Low-temperature measurements were made in an atmosphere of dry nitrogen with samples on a small liquid-nitrogen container which in turn was mounted on the cantilever beam.

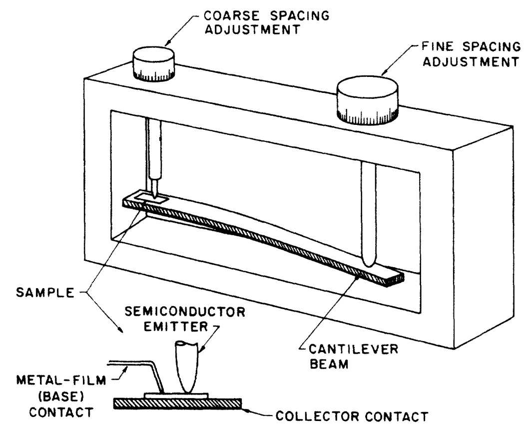

FIG. 1. Cantilever mechanism for fine adjustment of semiconductor emitter to metal-base spacing.

Au films of several thicknesses were deposited simultaneously by evaporation on chemically cleaned ⟨111⟩ Ge and Si surfaces in a Vac-Ion system at $\approx 10^{-8}$ Torr. Film thicknesses were measured by multiple-beam interferometry and a Taylor "Talysurf." The two measurements agreed within ±20 Å. A metal mask was used to define metal base regions ≈0.01 in. in diameter. The Si point had a radius of curvature of ≈0.001 in. The point was cleaned immediately before each set of measurements. The values of α were sensitive to the pressure of the point. The maximum α was obtained when the point just maintained contact with the Au film. The maximum values were reproducible and independent of the current for currents in excess of 0.5 mA.

Figure 2 shows the measured results. It is apparent that α varies exponentially with film

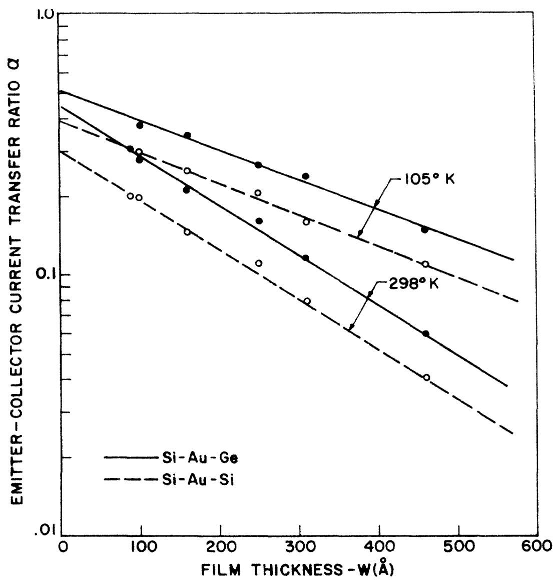

FIG. 2. Emitter-to-collector incremental current-transfer ratios in Si-Au-Si and Si-Au-Ge structures as a function of Au-film thickness at 298 and 105°K with collector electric fields of 3×10^4 V/cm.

thickness W:

$$\alpha = \alpha_0 \exp(-W/L_B). \tag{1}$$

L_B is interpreted here as the ballistic mean free path, i.e., the mean distance between scattering events in the metal for electrons injected from the Si emitter. These electrons have an average energy relative to the Fermi energy in the metal of ≈0.85 eV (the barrier height plus $2kT$ at 298°K), and ≈0.86 eV at 105°K (the barrier height itself is also temperature dependent[3]). α_0 is the current gain extrapolated to zero metal-base thickness. It is apparent that α_0 is different for the Si-Au-Ge and Si-Au-Si structures, and that both α_0 and L_B are functions of the temperature. The agreement between the theoretical and experimental values of L_B and α_0 and their temperature dependence will be considered below.

The present experimental results provide a convincing verification of theoretical estimates of the departures of α_0 from unity. The current-gain upper limit associated with optical-phonon scattering in the emitter and collector semiconductors,[4] α_P, and the quantum-mechanical transmission at the collector,[5] α_Q, determine $\alpha_0(=\alpha_P\alpha_Q)$. Table I shows that the agreement between the theoretical and experimental values of α_0(298°K) and α_0(105°K)/α_0(298°K) is satisfactory. The ratios of the values of α_0 at the two temperatures are virtually independent of the α_Q calculation.[5] The experimental data in Table I thus constitute an independent check of both theoretical calculations.[6]

Table II lists the values of L_B obtained from a least-squares analysis of the data in Fig. 2. Since the electrons were injected into the metal from similar emitters, the values of L_B for both the Si-Au-Ge and Si-Au-Si structures should be virtually the same. At both 105 and 298°K this was observed within the experimental error. The change in L_B with temperature can be accounted for as follows. Since any scattering in the metal virtually precludes collection of an injected electron,[7]

$$1/L_B = 1/L_P + 1/L_e, \tag{2}$$

where L_P is the electron mean free path for phonon scattering, and L_e is the mean free path for electron-electron, electron-defect, and electron-impurity scattering. L_e is expected to be essentially independent of temperature. L_P may be assumed to be close to the conductivity mean free path values of[8] 406 and 1150 Å for pure bulk gold at 298 and 105°K, respectively. These values and the measured values of L_B at 298°K were used in Eq. (2) to obtain the predicted low-temperature values of L_B and the L_e values in Table II. The agreement between the measured and predicted low-temperature values of L_B is satisfactory. A detailed interpretation of L_e will be presented in a future publication.

The above values of L_B appear generally consistent with those which can be estimated from a combination of thin-film resistivity measure-

Table I. Comparison of theoretical and experimental values of α_0(298°K) and α_0(105°K)/α_0(298°K).

Structure	α_0(298°K) Theory	α_0(298°K) Expt.	α_0(105°K)/α_0(298°K) Theory	α_0(105°K)/α_0(298°K) Expt.
Si-Au-Si	0.37 ± 0.10	0.31 ± 0.03	1.25 ± 0.03	1.28 ± 0.05
Si-Au-Ge	0.40 ± 0.10	0.46 ± 0.03	1.09 ± 0.03	1.08 ± 0.05

Table II. Mean free path values for ≈0.85-eV electrons in Au.

Structure	L_B (Å) 298°K	105°K	105°K(predicted)	L_e (Å)
Si-Au-Si	229 ± 7	357 ± 20	361 ± 14	525 ± 36
Si-Au-Ge	228 ± 11	387 ± 27	362 ± 28	520 ± 57

ments and measurements of the attenuation length of photoexcited electrons. There are, however, wide discrepancies in both the resistivity and the photoelectric measurements on which previous estimates of L_B are based.[9,10] Soshea and Lucas[9] show that when allowance is made for the difference between the optical absorption of thin Au films on glass and on Si, the photoelectric measurements by Crowell et al.[11] are in agreement with their own, but corresponding unpublished thin-film resistivity measurements by Crowell are in agreement with those of Sze, Moll, and Sugano.[10] Thus no two sets of measurements are consistent. The measurements of L_B reported here, however, are independent of any assumptions regarding the value or energy dependence of L_P or L_e.

In contrast with the point-contact emitter method described here, the method using sheet resistance and photoelectric measurements is much more laborious. The photoelectric measurements require careful calibration of the optical system to obtain the true photoresponse per absorbed photon, and a complex analysis of the transport problems involved.[9-12] The mean free path which is deduced is averaged over a much wider range of electron energies than in the point-emitter method for which the energy spread is of the order of kT. For metals in which the electron mean free path is comparable to the penetration depth of the illumination used in the photoelectric method, only a qualitative estimate of mean free path is possible. The point-contact method, on the other hand, is not subject to this limitation. Thus as a method for measuring the ballistic mean free path of excited electrons, the point-contact-emitter method is notable for its simplicity and the direct interpretation of the measurements.

[1]M. M. Atalla and D. Kahng, IRE, Trans. Electron Devices 9, 507 (1962).

[2]The essential features of the mechanism were designed by A. V. Voiner. The mechanism was obtained on loan from H. N. Wagar.

[3]C. R. Crowell, S. M. Sze, and W. G. Spitzer, Appl. Phys. Letters 5, 91 (1964).

[4]C. R. Crowell and S. M. Sze, to be published.

[5]C. R. Crowell and S. M. Sze, in IEEE Solid State Device Research Conference, Princeton, New Jersey, June, 1965 (to be published); also, C. R. Crowell and S. M. Sze, to be published.

[6]In the "symmetrical" structure (Si-Au-Si) the incoming electrons do not possess enough kinetic energy near the collector potential-energy maximum to produce an optical phonon [C. R. Crowell and S. M. Sze, Solid State Electron. 8, 673 (1965)]. In this region, scattering thus proceeds by optical-phonon absorption and is strongly temperature dependent. In the collector of the "asymmetrical" (Si-Au-Ge) structure, scattering may proceed by both generation and absorption and is not strongly temperature dependent. The theoretical predictions of α_P for the Si-Au-Si structure are 0.68 and 0.85 at 298 and 105°K, respectively.[4] The corresponding values of α_P for the Si-Au-Ge structure are 0.55 and 0.60.[4]

[7]Crowell and Sze, reference 6.

[8]N. F. Mott and H. Jones, The Theory of the Properties of Metals and Alloys (Dover Publications, New York, 1958), p. 268.

[9]R. W. Soshea and R. C. Lucas, Phys. Rev. 138, A1182 (1965).

[10]S. M. Sze, J. L. Moll, and T. Sugano, Solid State Electron. 7, 509 (1964).

[11]C. R. Crowell, W. G. Spitzer, L. E. Howarth, and E. E. LaBate, Phys. Rev. 127, 2006 (1962).

[12]R. Stuart, F. Wooten, and W. E. Spicer, Phys. Rev. 135, A495 (1964).