it appears to be clear from the experiments that the confinement time for a plasma with $\beta < 1$ can be markedly increased by $M+S$-like configurations.

These investigations are being extended to higher energies ($B_{max} \approx 40$ kG), using a vessel and coils shaped to an $M+S$-like geometry.

We would like to express our gratitude to Professor A. Schlüter, who greatly advanced this work through many stimulating discussions. We are likewise indebted to Dr. G. V. Gierke for his continuous support, and to Dr. H. U. Schmidt and Dr. D. Pfirsch for many stimulating and valuable discussions.

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MEAN FREE PATH OF HOT ELECTRONS AND HOLES IN METALS*

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Knowledge of the mean free path of hot electrons in solids is of considerable interest and importance. Recently, Crowell, Spitzer, and their coworkers have measured the attenuation length of hot electrons[1,2] in Au, Ag, Cu, and Pd and of hot holes in Au.[3] From a fundamental point of view, the principal importance of these measurements lies in the information which may be derived from them concerning the mean-free-path lengths for electron-electron scattering. The difficulty in obtaining mean free paths from attenuation lengths is due to the fact that neither diffusion theory nor age theory is adequate for problems in which the initial source is concentrated within a few mean free paths of the surface,[4] as is the case here. However, as has been well demonstrated in the treatment of similar problems in neutron physics, the problem can be treated as accurately as necessary by the application of the Monte Carlo method.[5] It is the purpose of this paper to report on such calculations made for the systems[6] studied by Crowell, Spitzer, and their co-workers.[1-3]

Using the Monte Carlo method,[7] the photoyield was calculated as a function of film thickness for the geometry used by Crowell et al. In doing this, the exponential spatial distribution of the optical absorption was taken into account and the assumptions listed below were made. The probability of an electron being excited into a state with energy between $h\nu + E_F$ and $\phi + E_F$ was taken to be independent of the energy of the states involved. Here E_F is the energy of the Fermi level, ϕ is the height of the metal-semiconductor barrier, and $h\nu$ is the photon energy. Only scattering by phonons and other electrons was considered. Due to the large energy loss involved in electron-electron scattering, an electron was assumed to have zero escape probability after such an event. The direction of motion of the electron was taken to be isotropic following excitation and each subsequent phonon-electron scattering event. The reflection of electrons at the surface was taken to be spectral. All the electrons with sufficient momentum to escape were assumed to do so, i.e., the reflection coefficient for these electrons was taken to be zero.

Figure 1 gives the calculated photoyield as a function of the thickness of the metal film for a photon energy of 1.015 eV, a barrier height of 0.79 eV (corresponding to that of Au on Si),[1,3] and for values of 500 and 1000 Å for the phonon-electron mean free path l_p and electron-electron

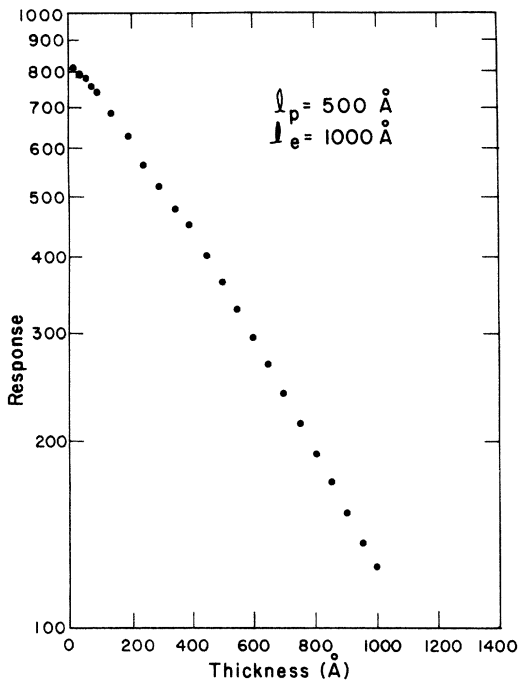

FIG. 1. Number of electrons escaping as a function of metal film thickness for 10^4 electrons initially excited above the barrier height. For this case, l_p = 500 Å, l_e = 1000 Å, $h\nu$ = 1.015 eV, ΔE_p = 0.001 eV, and the optical absorption constant, α, is 7.7×10^5 cm^{-1}.

mean free path l_e, respectively. The average energy loss per phonon-electron scattering event, ΔE_p, was taken to be 0.001 eV. This curve is typical of most of the others obtained in this work in that it can be approximated by an exponential (giving a well-defined attenuation length) within the accuracy of the experiments. Only for the extreme case of a large energy loss (e.g., 0.03 eV) per phonon-electron interaction did the curve depart significantly from an exponential.

To determine l_e from data giving the attenuation length L, values must be assigned to l_p and ΔE_p. For metals, l_p is known only for those electrons at the Fermi energy; the values for these cases are: Au–415 Å, Ag–560 Å, and Cu–720 Å. The mean free path for more energetic carriers might be expected to be somewhat less.[8] Fortunately, it is possible to analyze the experimental data in some detail without having exact knowledge of l_p. Calculations were made for values of ΔE_p of 0.001, 0.005 eV and, for a few representative cases, for 0.01 and 0.03 eV. Since the attenuation length was found to be practically independent of ΔE_p, the choice of ΔE_p did not affect the calculations presented here. However, it was found that the yield decreased with increasing ΔE_p for $\Delta E_p > 0.005$ eV, and that for $\Delta E_p = 0.03$ eV the plot of ln(photoyield) versus thickness became much more convex than the example given in Fig. 1, and thus deviated significantly from an exponential. For Cu, which has the highest Debye temperature ($k\Theta \approx 0.03$ eV) of the metals studied, the experimental curve plot was also quite convex. It should be noted that, in principle, if both the attenuation length and the absolute photoyield were determined experimentally, both l_p and l_e could be determined from the experimental data through the type of analysis used here.

By calculating the yield for thicknesses of 200, 400, 600, 800, and 1000 Å, attenuation lengths were obtained as functions of l_e and l_p for photon energies of 1.1, 1.015, and 0.952 eV with a barrier height of 0.79 eV (corresponding to the experimental situation[1,2] for Au on n-type silicon), and for a photon energy of 0.80 eV and a barrier height of 0.70 eV (corresponding[3] to Au on p-type GaP). In these calculations, a "test sample" of at least 10 000 electrons was used for each point, with an error less than 2%. The differences in the results obtained using these various values of $h\nu$ and ϕ were negligible compared to the estimated experi-

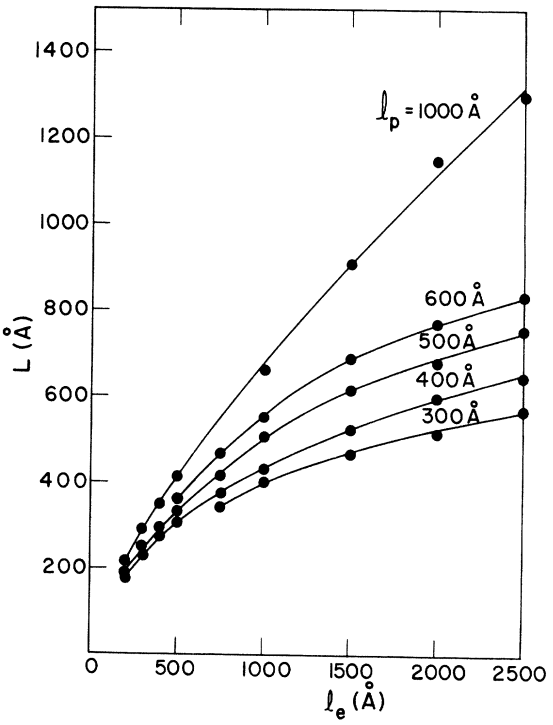

FIG. 2. Calculated attenuation length, L, as a function of the electron-electron mean free path, l_e, for various values of the mean free path, l_p, for scattering of electrons by phonons.

mantal errors.[1-3] Since the calculation depends only on the quantity $h\nu - \phi$, and not on the absolute values of $h\nu$ and ϕ, the calculations for Au are applicable to the measurements made on Ag, Cu, and Pd.

The results of these calculations are given in Fig. 2. Two fairly well-defined ranges of L and l_e can be distinguished. For $l_e < 350$ Å and $L < 300$ Å (region 1), L is a fast function of l_e and depends much less strongly on l_p; whereas, for $l_e > 500$ Å and $L > 400$ Å (region 2), the converse is true.[9] In region 1, L and l_e approach each other fairly closely in value; whereas, for region 2, l_e is considerably larger than L.

The values of l_e obtained from the experimental values of L for the various metals are given in Table I. The values of l_p can only be estimated to within certain limits; correspondingly, it is only possible to determine the limits within which l_e lies. A striking thing about the values of l_e is the large variation from metal to metal. For Au the values of l_e for both electrons and holes are over 1000 Å. It should be noted that l_e will only be decreased appreciably by an increase of l_p to 1000 Å or more. Such large values of l_p seem quite unreasonable. Since L for these materials lies in region 2, it is not highly dependent on l_e and it is difficult to obtain very precise values on the upper limits; however, they are certainly less than 10 000 Å. For Ag, l_e is also relatively large ($700 < l_e < 2500$ Å); whereas, for Cu and Pd, the values of l_e are much smaller (a few hundred Å).

Also given in Table I are the theoretical values for l_e obtained from the equation of Quinn.[10,3] There is no close agreement between these values and those obtained by this analysis from the experimental attenuation lengths, although the values for Cu and Pd are in much closer agreement than those for Au and Ag. This may be due to the lack of knowledge of the parameters necessary for the application of Quinn's theory rather than to a fundamental defect in the theory.

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[6]The method used here is being applied to similar problems for which data are available, including secondary emission, and will be published.

[7]Details of the calculation will be published elsewhere.

[8]The occurrence of other scattering mechanisms, e.g., those due to lattice defects or impurities, could probably also be taken into account by means of a reduced mean free path for l_p.

[9]This is physically reasonable. If l_e, l_p, and L are comparable in value, L will depend principally on l_e since an electron does not escape after an electron-electron collision. However, as l_e becomes larger compared with l_p, the electron will suffer a number of phonon scattering events before escaping and l_p will become quite important in determining L.

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Table I. Values of the electron-electron mean free path, l_e, obtained from the experimentally determined (references 1, 2, and 3) attenuation lengths, L. The third column gives the values of the l_p used. The fifth column gives the theoretical value, $l_{e,t}$, for the electron-electron mean free path as given by the theory of Quinn (references 2 and 10).

Material	L (Å)	l_p (Å)	l_e (Å)	$l_{e,t}$ (Å)
Au (electrons)	740	≤ 500	> 2000	406
Au (holes)	550	≤ 500	> 1000	520
Ag (electrons)	440	$100 \leq l_p \leq 600$	$700 \leq l_e \leq 7500$	570
Cu (electrons)	$50 < L < 200$	$100 \leq l_p \leq 800$	≤ 250	421
Pd (electrons)	170	$100 \leq l_p \leq 800$	$150 \leq l_e \leq 400$	110