The additional single point (Δ) plotted in Fig. 2(a) represents a stable plasma (decaying solely by charge exchange) observed when the injected beam was turned off after a period of violent instability. The plasma is typically stable during such decay periods even at densities well above the threshold line of Fig. 2 (see, for example, Fig. 3 of Ref. 3). A measured transient increase in electron energy during the decay[12] does not seem to be sufficient by itself to account for the large shift in stability level observed. The change in stability level may be attributed to a broadening of the trapped-particle distribution by the action of the instability. Evidence for the energy spreading of the ions under these conditions has been reported,[3] and one expects a similar smoothing of the angular and spatial distributions to occur. The observed enhanced stability could result from a reduced ion-driving term for the instability, from reduced wave reflections (allowing damping to occur in the outer regions of the plasma), or from a combination of these effects, including the transient increase in electron temperature.

In summary, the above interpretation of our threshold measurements accounts quantitatively for data taken over a wide range of experimental parameters. The results lend support to theories of wave-damping effects in mirror-confined plasmas.[11] These same theories point the way to the achievement of stably confined plasma at high density.

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INVESTIGATION OF COLLECTIVE ELECTRON OSCILLATIONS IN Cd, Mg, AND Zn BY PHOTOEMISSION

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The plasma resonance in films of Mg, Zn, and Cd, was measured by observing the associated peak in photoemission. For Mg, the plasmon energy of 10.21 eV and lifetime of 1.09×10^{-15} sec agree with values obtained by energy-loss and optical techniques. For Zn and Cd the plasmon energies are 9.46 and 8.68 eV, respectively. The lifetimes of 1.14×10^{-15} sec and 0.82×10^{-15} sec, for Zn and Cd, respectively, are considerably larger than previously observed.

The optically induced plasma resonance[1] provides a direct method of observing the collective oscillations of electrons in metals. Since the resonance is investigated by optical means, a high resolution is more easily obtained than by the earlier methods of observation which determined the discrete energy loss of fast electrons. The measurement of the optical constants from reflectivity data also allows the loss function to be calculated. Although using optical methods,

this procedure has the disadvantage that it is an indirect method, since the bulk reflectance around the plasma frequency is a relaxation rather than a resonance. A direct method of observing the optically induced plasma resonance occurring in thin films is by measurement of the peak in the photoelectric yield. This resonance peak has been observed by several authors,[2-6] but no quantitative measurements have yet been reported. In this work the plasmon energy and lifetime were determined from the photoemission of thin films of Cd, Zn, and Mg. The values are compared with those obtained from the optical constants, energy-loss, and plasma radiation measurements.

The plasma parameters were determined by scanning with p-polarized light, for several angles of incidence, the relative photoelectric emission of the thin metallic film over a wavelength region around the plasma resonance. The curves were normalized with the curve measured at normal incidence. The width of this resonance is determined by two lifetime constants, the intrinsic damping rate τ_d and the radiative mean life τ_r. The latter depends on the angle of incidence θ according to[7]

$$\tau_r^{-1} = (\omega_p^2 t/2c)\sin\theta\tan\theta \qquad (1)$$

with $\omega_p = 2\pi c/\lambda_p$ the plasma frequency, and t the film thickness. The real part of the resonance frequency is given by[8]

$$\mathrm{Re}(\omega) = \omega_p\left(1 + \frac{\omega_p^2 t^2}{8c^2}\tan^2\theta\right). \qquad (2)$$

The plasma frequency and the intrinsic damping parameter can therefore be found by determining the width and peak frequency of the resonance as a function of the angle of incidence and then extrapolating to zero angle. This method, applicable where $\hbar\omega_p$ exceeds the work function of the metal, avoids the error sources normally present in similar measurements. In this case absolute intensities are not required and no difficulty due to beam nonuniformity is encountered as in the reflectance method. Though the samples should be illuminated with p-polarized light, the degree of polarization is unimportant. Photoelectric factors like penetration probability and diffusion length of excited electrons are excluded. No ambiguities due to interband transitions, higher losses, or surface plasmons are encountered. Therefore the wrong assignment of the plasmon energy, for example in Zn and Cd, by Robins[9] and Bakulin et al.,[10] and in Zn by Cook and Cundy,[11] is avoided.

The difficulties of the method originate from preparation problems, since a film thickness small compared with $\lambda_p/2\pi$ is required. In these experiments, films of about 50 Å thickness have been used. The structure of such thin films is very much in doubt,[12] and it might well influence the plasma resonance, since all three materials are optically anisotropic. To check this problem, films of about 1000 Å thickness were evaporated onto the same substrates and the reflectance at normal incidence was determined. Good agreement was observed for Zn and Cd between the measured curves and the reflectance curves calculated from a Drude model using the parameters extracted from the photoemission experiments. The reflectance curve for Mg fitted a calculated curve with the plasma frequency shifted about 0.3 eV to higher energies. Together with the anomalous dispersion behavior of Mg as shown below, this points to a partly oriented growth of the 50 Å films.

An example of the experimental curves is shown in Fig. 1 for a 44-Å Cd film on fire-polished Pyrex. This film was typical in being deposited in a vacuum of about 10^{-9} Torr and measured in a vacuum of 10^{-10} Torr. The peak value for this Cd film increases with increasing angle, but for larger angles it decreases again, while the width continues to increase. The highest peak is obtained for 45° or smaller angles, depending on damping and film thickness. Peak values of up to 22 have been measured with thin Mg films, which has led to its consideration as a detector

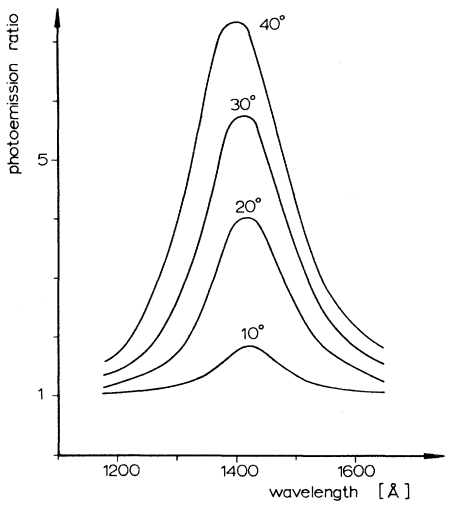

FIG. 1. Photoemission ratio of a 44-Å Cd film for several angles of incidence. Each curve has been normalized with the normal-incidence curve.

of polarized uv radiation. With Zn films, factors up to 4 are observed. The evaluation of the photoemission ratio curves is shown in Fig. 2 for Cd, Mg, and Zn. Figure 2(a) shows the extrapolation of the halfwidths according to Eq. (1). From the slope the thickness of the film may also be derived. For these films the thickness was 39 Å for Cd, 78 Å for Mg, and 50 Å for Zn. These values are in fairly good agreement with those obtained from the quartz-crystal thickness monitor, calibrated using the bulk densities, which gave thicknesses of 44, 80, and 60 Å for Cd, Mg, and Zn, respectively. Figure 2(b) shows the extrapolation of the dispersion according to Eq. (2). The Cd film exhibits approximately the behavior predicted by this equation, while the Zn film shows no dispersion at all. With the Mg film a rather strong dispersion is observed, but of opposite sign. The optical constants[19] of Mg around the plasma wavelength do not show any deviation from the Drude theory which could explain the observed dispersion. It is believed that this anomalous behavior is the result of a partial orientation in the growth of the thin Mg film, resulting in an optical anisotropy.

A comparison is given in Table I between the present work and results obtained earlier by energy-loss experiments, reflectance measurements, and plasma radiation measurements. For Cd, Mg, and Zn, the energy of the resonance peak as well as the relative width is listed. The latter is related to the lifetime of the plasmon by $\Delta E/E = (\omega_p \tau_d)^{-1}$. Except for the value due to Sueoka,[13] the relative widths of the energy-loss data have been determined from the width of the loss curves and are not corrected for the width

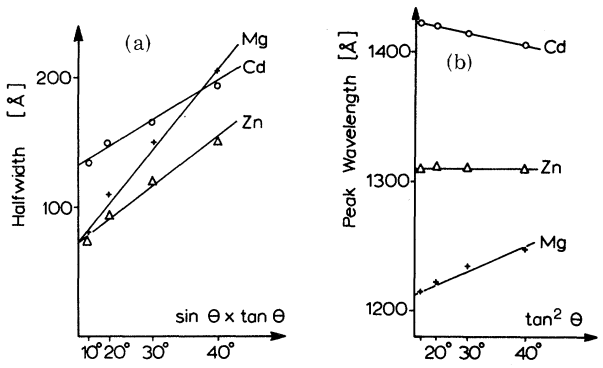

FIG. 2. Extrapolation of the photoemission values for Cd, Mg, and Zn to zero angle of incidence. (a) Plot of half width; (b) plot of peak frequency (dispersion).

Table I. Comparison of results with energy-loss, optical, and plasma radiation measurements.

	Cd			Mg			Zn		
Experiment	Resonance Peak (eV)	$\frac{\Delta E}{E}$	Ref.	Resonance Peak (eV)	$\frac{\Delta E}{E}$	Ref.	Resonance Peak (eV)	$\frac{\Delta E}{E}$	Ref.
Energy Loss	7.5	.35[a]	(9)	10.5	.09[a]	(17)	8.6	.32[a]	(9)
	7.8	.32[a]	(14)	10.2	.059	(13)			
Optical	8.55	.65[b]	(15)	10.6	.125[b]	(18)	9.6	.42[b]	(22)
(Reflectance)				10.5	.062[b]	(19)	9.5	.40[b]	(23)
							9.15	1.5[b]	(21)
Plasma Radiation	9.1	.13[a]	(16)	8.85	.21[a]	(20)	Shoulder only		(16)
Photoemission (Present work)	8.68	.092		10.21	.059		9.46	.061	
Plasmon lifetime	0.82×10^{-15} sec			1.09×10^{-15} sec			1.14×10^{-15} sec		

[a]Derived from the width of the loss curve, not corrected for primary beam width or angle.
[b]Inverse of the peak value of the loss function.

of the primary beam. The values of the optical experiments are from the loss curves, $\mathrm{Im}1/\epsilon$, given by the authors. The peak energy is listed in the first column, while the inverse of the peak value $\mathrm{Im}1/\epsilon(\omega_p)$, equal to $\epsilon_2(\omega_p)$, is listed as the relative width.

The energy-loss data of Robins[9] and Powell[14] for Cd peak at energies about 1 eV lower than observed in this work. The reflectance measurement of Jelinek et al.[15] had been performed on films exposed to air, therefore their loss function indicates a very broad resonance. The plasma radiation measurement of Herickhoff et al.[16] shows a width very near to the one measured by photoemission. An extrapolation to zero angle, which is not possible there since only one angle (30°) has been measured, would bring the value even nearer to the value obtained by photoemission. For Mg complete agreement is found with the energy-loss measurement of Sueoka,[13] while the loss function determined by Daudé et al.[18] suggests higher damping. A very recent measurement by Daudé et al.,[19] performed in ultrahigh vacuum, gives the same width for the loss function as is found from the photoemission measurement. The plasma radiation measurement of Arakawa et al.[20] shows a very much broadened peak shifted to longer wavelengths. A similar shifting and broadening was observed in the present experiment with Mg films that showed a relatively high film resistance after deposition and were therefore believed to have an insular structure.

As in the case of Cd, the loss peak for Zn as observed by Robins[9] is found to be broader and at lower energies. Several optical measurements have been published for Zn. The films of Jelinek[21] had been exposed to air prior to the measurement. Lemonnier et al.[22] used Zn films evaporated in situ, while Mosteller and Wooten[23] determined the reflectance of the basal plane of a Zn crystal cleaved in ultrahigh vacuum. It is surprising that the loss function of these two measurements nearly coincides, since the latter observed much higher reflectance at energies below the plasmon energy. Also the curve for normal-incidence reflectance given by Mosteller and Wooten[23] suggests a much lower relative width than obtained from their loss function. In the plasma radiation measurement of Herickhoff[16] a shoulder instead of a peak is observed in the emission.

The last line in Table I gives the plasmon lifetimes as calculated from plasmon energy and relative width. Except for Mg, where agreement is found with the measurements by Sueoka[13] and Daudé et al.,[19] the lifetime is considerably larger than previously assumed. The metals Cd, Mg, and Zn are seen to have a relative plasma resonance width comparable to that of aluminum and the alkali metals. The values given here have to be considered as lower limits for the lifetime, since they are determined using polycrystalline films, and possibly the resonance is even sharper for certain directions in a single crystal.

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