ter blocking model" for spin-glasses[12] is an appropriate description for our anomalous magnetic ordering in $EuS_{0.1}Se_{0.9}$. The ferromagnetic, strongly exchange-coupled Eu(111) planes can be regarded as the clusters which are blocked at low temperatures by weak interplanar interactions.

For $J_1 \neq -J_2$ ($y \neq 0.1$) there is an effective exchange coupling between the Eu(111) planes, and the compounds concentrated in Eu show long-range magnetic ordering (antiferromagnetic for $J_2 < -J_1$, ferromagnetic for $J_2 > -J_1$). But nevertheless the interplanar coupling is rather weak for J_2 close to $-J_1$ and it is expected to be most heavily disturbed on introduction of fluctuations of the exchange interactions by replacement of Eu by diamagnetic Sr. Thus we think the magnetic structure of the spin-glass state for the Sr-diluted samples with $J_1 \neq -J_2$ is similar to the one described above.

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Long-Range Surface-Plasma Waves on Very Thin Metal Films

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(Received 17 August 1981)

The dispersion equation of injected surface-plasma waves that propagate on thin metal films has been solved as a function of the film thickness, and splitting of the modes into two branches is observed. For one branch the imaginary part of the propagation constant goes to zero as the thickness of the metal decreases. Reflectivity calculations agree with this result, which predicts that one can obtain propagation distances that are more than 1 order of magnitude larger than observed before.

PACS numbers: 73.60.Dt

The lifetime or decay constant of a surface-plasma wave (SPW) that propagates on a metal surface is an important physical quantity because it is a strong function of the properties of the metal surface, and can therefore serve as a sensitive probe for characterizing surface conditions such as roughness and composition.[1-4] There is only one SPW mode for thick metal films, and the upper limit of its propagation range is determined by the complex refractive index of the metal and the loss introduced by the medium bounding the metal.[5]

The existence of two thermally excited SPW modes, one symmetric and one antisymmetric, that propagate on an unsupported thin metal film (the two media bounding the metal film are identical) has been discussed theoretically and verified experimentally by using electron scattering techniques.[6,7] The theory that predicted the existence of these two modes did not treat the problem of their lifetime and optical-wavelength dependence, and since the resolution and signal-to-noise ratio of the experiments were low, the linewidth of these modes could not be measured.

A comprehensive analysis of the dispersion of SPW that propagate on various combinations of thin metal films sandwiched between thin dielectric films revealed the existence and splitting of the SPW modes as the metal thickness decreases.[8,9] The theory dealt only with the dependence of the real wave vector on the real part of the frequency, and did not treat the properties of the imaginary part of the frequency, which is associated with the lifetime of the thermal SPW.

The theory of the dispersion and lifetime of thermal SPW that propagate on supported or unsupported thin metal films has been discussed by Fukui, So, and Normandin.[10] Their theoretical conclusion was that, for an unsupported metal film, there is a SPW mode that has a lifetime which increases as the thickness of the metal film decreases, while for the supported metal film such a mode does not exist.

In this Letter a different case is treated, namely that of "injected" SPW, where the frequency is a real quantity, while the wave vector is complex. It is shown that for both the supported and unsupported metal films one can excite a SPW mode having a decay constant that goes to zero as the film thickness becomes small enough, and that this mode can exist even in the visible range of the spectrum. The reflectivity at the base of a prism that is placed close to a thin metal film has also been calculated with identical results. The theory of the splitting of the SPW modes and their properties and means of excitation is discussed; this long-range mode offers a unique opportunity for probing the characteristics of metal surfaces.

The geometry of the thin metal film that is coupled to a prism, and that supports the SPW, is shown in Fig. 1, where n_0, $n_1 = n' + in''$, n_2, and n_3 are the refractive indices of the substrate, metal film, gap, and prism, respectively, and t and s are thicknesses of the metal and the gap, respectively.

The standard dispersion relation for a free TM mode ($s \gg \lambda$) that is guided by a thin dielectric, semiconductor, or metal film, is given by[11]

$$K\beta t = \tan^{-1}(k_{10}) + \tan^{-2}(k_{12}) + m\pi, \qquad (1)$$

where $K = 2\pi/\lambda$, λ is the free-space optical wavelength, $k_{10} = \epsilon A/n_0^2 B$, and $k_{12} = \epsilon C/n_2^2 B$. Here $A^2 = \beta^2 - n_0^2$, $B^2 = n_1^2 - \beta^2$, $C^2 = \beta^2 - n_2^2$, $K\beta$ is the propagation constant of the guided wave, $\epsilon = n_1^2$, and m is the mode number. Equation (1) is an implicit complex equation in the complex variable $\beta = \beta' + i\beta''$, where β' is related to the speed of the mode by $v = c/K\beta'$, and β'' is related to the amplitude attenuation of the mode by $\alpha = K\beta''$.

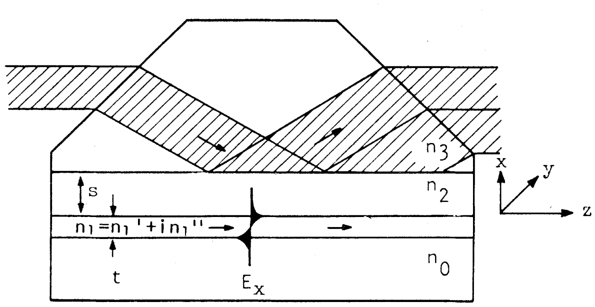

FIG. 1. The geometry of the prism to surface-plasmon wave coupler. Note the antisymmetric (transverse) electric field distribution of the long-range mode.

A considerable simplification in the solution of Eq. (1) can be made by defining

$$k = (k_{10} - i)(k_{12} - i)/(k_{10} + i)(k_{12} + i). \qquad (2)$$

From Eqs. (1) and (2) one obtains the real implicit dispersion relation with real variables

$$\tan[(\beta'/\beta'')\ln|k|] + k''/k' = 0, \qquad (3)$$

where k' and k'' are the real and imaginary components of k, respectively. To solve Eq. (3), one chooses a value for β', and then searches for the value of β'' such that Eq. (3) is satisfied. Consequently, one has to use complex numbers only for the evaluation of A, B, C, and k; a simple computer routine will solve for β''. The film thickness is obtained by

$$t = -\ln|k|/2K\beta''. \qquad (4)$$

All the modes we are considering here have a mode number $m = 0$. By using Eq. (1) it is possible to generate curves of the interdependence of the three variables β', β'', and t, for a given set of refractive indices. These calculations have been carried out for various combinations of parameters at optical wavelengths extending from the visible to the far infrared.

For a thick, unsupported metal film, in which the two bounding media are identical, the speed and decay constant of the SPW's on each one of the interfaces are the same. Each one of these two SPW's has an evanescent wave extending both into the dielectric medium and into the metal film. If the metal film is thick enough, the evanescent waves inside the metal that belong to the two SPW's do not overlap. As the film thickness decreases, the evanescent waves of the otherwise decoupled modes begin to overlap, and a transverse standing wave is established. The degenerate SPW mode therefore splits into one symmetrical and one antisymmetrical mode (referring to the transverse electric field distributions). These symmetric and antisymmetric modes are characterized by a range that increases and decreases, respectively, as the film thickness decreases.

For a thick, supported metal film, in which the two bounding media are not identical, the modes that propagate on each one of the two interfaces have different speeds and decay constants and their evanescent fields inside the metal do not overlap. As the metal thickness decreases, these evanescent fields begin to overlap, and each one of these two modes splits into two branches, as in the unsupported case, one having a decreasing range and one having an increasing one. In the supported metal film case, however, extra interfering terms between the two evanescent waves inside the metal will limit the range of the antisymmetric mode if the difference between the refractive indices of the two media bounding the metal is too large.

In Fig. 2 the dependence of β' (dashed lines) and β'' (solid lines) on the metal thickness t is shown for the case of the free SPW. The parameters used are $n_0=1.5$, $n_1=0.0657+i4$ (Ag), $n_2=1.55$, and $\lambda=6328$ Å. One observes the decrease in both β' and β'' for the antisymmetric mode as t decreases. The physical validity of the results of these calculations has been verified by checking the value of the evanescent propagation constants, A and C, for each resultant β', β'', and t, to insure that the SPW is actually confined to the thin metal film. For each case the magnitude and phase of the electric and magnetic fields across the thin metal film has been calculated. The absolute value of the (unscaled) magnetic field $H_y(x)$ is shown in Fig. 3 for the metal film that is in the y-z plane with a thickness $t=200$ Å. In (a), $\beta=1.5507+i0.0001615$, $A=0.39+i0.00064$, and $C=0.047+i0.0053$. Outside the film, the field is evanescent, while in the film it obtains a small dip. In (b), $\beta=2.14+i0.0325$, $A=1.53+i0.046$, and $C=1.44+i0.059$, and the field obtains a value of zero at about the center of the film. There are two electric fields, $E_z(x)$ and $E_x(x)$, the first being proportional to $H_y(x)$ in each one of the three regions and for the two modes. The second field is proportional to the derivative of $H_y(x)$ with respect to x in each one of the three regions, with (a) and (b) interchanged. One observes that in (a) the evanescent fields penetrate the media bounding the film much deeper than in (b). It is assumed that the only loss the SPW suffers is due to the dissipation of power inside the metal film. Since the mode in (a) has a smaller fraction of its field inside the metal than mode (b) has, it will have a larger propagation range.

In order to assess the feasibility of exciting this long-range mode, the reflectivity at the base of the prism, as shown in Fig. 1, has been calculated for the same material parameters used for the free SPW. It was found that in order to observe the extremely narrow dip in the reflectivity, which is associated with the excitation of the long-range mode, one has to scan across the angle of incidence of the input beam with a very high resolution. Since this mode has a large evanescent field, the angle for optimum excitation is close to the critical angle. As a result, small changes in the incidence angle produce

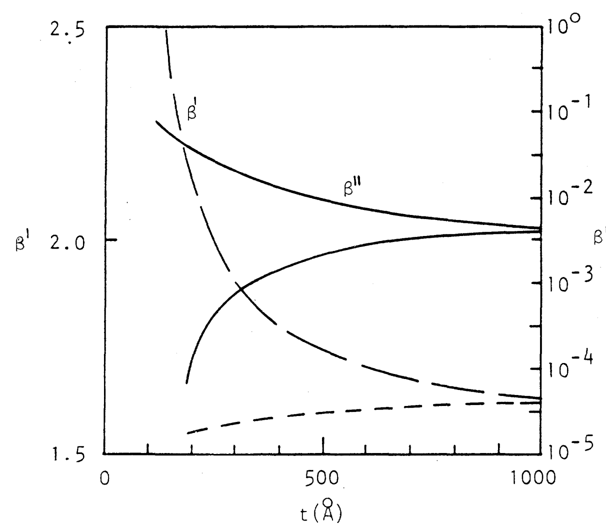

FIG. 2. The real ($K\beta'$) and imaginary ($K\beta''$) propagation constants of a surface-plasma wave propagating on a thin Ag film. Here $n_0=1.5$, $n_2=1.55$, $\lambda=6328$ Å, and $s\gg\lambda$. Note that the decay constant $\alpha=K\beta''$ goes to zero as the metal film thickness decreases.

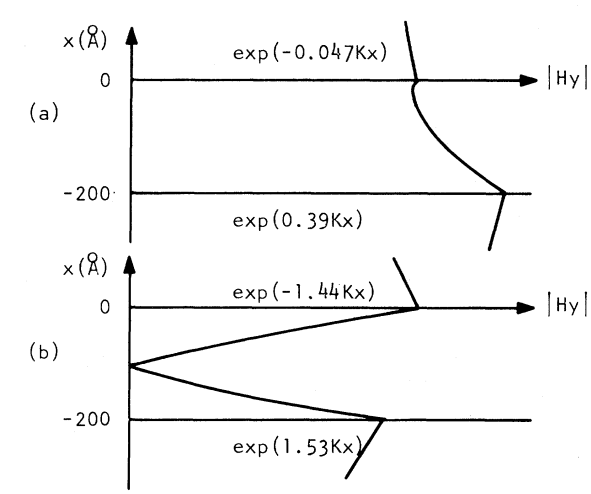

FIG. 3. The absolute value of the transverse magnetic field distribution of the (a) long-range and (b) short-range modes (not to scale.)

large changes in the penetration depth of the evanescent fields. For each angle of incidence, therefore, the gap thickness s has to be adjusted so that the proximity of the prism will have exactly the same damping effect on the otherwise freely propagating SPW. If s is too large, the excitation will be inefficient, while if s is too small, the proximity of the prism will load and wipe out the SPW.

Reflectivity calculations with use of the same parameters as in Fig. 2 yield, for a metal thickness of 200 Å, the following results: The critical angle is 32.6244°, the angle at maximum absorption is 32.6414° and the half-width angle is 0.004°. The distance which the long-range mode propagates on the 200 Å thin film until its power decays by a factor of $1/e^2$ is therefore 300 μm, which is 27 times larger than for a SPW that propagates on the surface of a thick Ag slab. Since the range of this mode is very large, its study in the case that the surfaces are randomly rough can provide useful quantitative information about roughness-induced attenuation. As a result, this mode can be used as a probe for characterizing the properties of surfaces and thin metal films. This long-range mode can also be utilized for nonlinear interactions such as second-harmonic generation where the nonlinearity is introduced by the metal itself or by the bounding media via the evanescent fields. By imbedding the thin metal film in an (optical) power-dependent refractive-index semiconductor, one obtains for the long-range SPW a power-dependent propagation-constant which can be used for bistability studies.[12]

In summary, this theory predicts that it is possible to choose material and geometrical parameters such that a long-range SPW mode could be excited on a thin metal film, the range being more than 1 order of magnitude greater than observed before. This mode can be used for the study of rough surfaces and various nonlinear interactions where a large interaction range is desirable.

Useful discussions with G. I. Stegeman and A. Craig are acknowledged. This work is supported by the Air Force Office of Scientific Research, U. S. Air Force, and the Army Research Office, U. S. Army, under Contract No. JSOP F49620-80-C-0022.

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Collective-Flux-Pinning Phenomena in Amorphous Superconductors

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(Received 23 October 1981)

The pinning force F_p in amorphous Nb_3Ge films with $T_c \sim 4$ K has been measured as a function of perpendicular field, temperature, and thickness of the samples. As a result of the large κ and low J_c characteristic of amorphous superconductors the pinning force for the first time is found to be in good agreement with the theory of Larkin and Ovchinnikov for collective pinning extended to the two-dimensional case. Pinning-mediated renormalization of the shear modulus leads to a sharp peak in F_p near the upper critical field.

PACS numbers: 74.60.Ge, 74.70.Lp

The theory of collective pinning of the flux-line lattice (FLL) as first proposed by Larkin and Ovchinnikov[1] (LO) is based on a very attractive physical concept, which has been known in the literature for ~10 years. Until now, it has not been verified experimentally. Collective pin-

