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STRUCTURE OF THE SPIN POLARIZATION SPECTRUM OF SECONDARY ELECTRONS EMITTED FROM NICKEL

by

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ABSTRACT

The main features of the structure observed in the energy resolved spin polarization of secondary electrons emitted from Ni are interpreted in terms of surface and bulk plasmon assisted emission. The model also predicts a measurable shift of the main polarization peak of about 0.3 eV to lower energies as the temperature is raised from room temperature to closely below the Curie temperature.

Key-words: Secondary electrons; Polarized electrons; Plasmons; Nickel; Transition metals.

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The energy resolved spin polarization, P(E), of the secondary electron emission from Ni(110) has recently been measured by Hopster et al.[1]. At lowest kinetic energy P(E) reaches a maximum of ∿17%, which is about three times larger than the mean conduction band polarization (∿5.5%). Within about 3 eV towards higher kinetic energy the spin polarization decreases to about 8%, and displays pronounced structures at higher energies. The polarization increase towards lower kinetic energies has been explained by Penn et al.[2] in terms of a spin asymmetry of the electron mean free path. The scattering cross section of minority spin electrons is larger than that of the majority spin electrons due to the availability of a high density of empty minority spin states close to the Fermi energy[3]. The relative contribution of these empty states to the scattering probability becomes larger as the initial electron energy approaches the Fermi surface, thereby enhancing the spin asymmetry. This effect alone, however, cannot account for the overimposed structure observed in the polarization spectrum[1,2], in particular for the pronounced peak at ∿16 eV. Here it is shown that the main features of that structure may result from the contribution of the highly polarized electrons which, although having low energy (even below the vacuum level) are emitted after being inelastically scattered by collective excitations (plasmons).

A simple model is considered in which the energy of a plasmon is transferred to an electron while conserving its initial spin orientation[4]. Momentum conservation is relaxed in virtue of the flatness of the plasmon dispersion and the proximity of the surface, and no attempt to a detailed description of the subsequent electron escape is made. An incoming high energy electron beam incides on the metal surface producing a steady state distribution $\rho_\sigma(E)$ of excited electrons. The energy E is measured from the vacuum level and σ denotes the spin direction. The beam also produces collective excitations (plasmons) whose characteristics can be determined from electron energy loss spectra[5]. The theory of the electron cascade leading to the distribution $\rho_\sigma(E)$ and its connection with the current of secondary electrons has been developed by Wolff[6]. Here we explicitate a relatively small contribution to the secondary electron emission arising from the electron-plasmon interaction whose effect on P(E) is, however, greatly amplified. The energy distribution of the secondary electrons, $N_\sigma(E)$, is then approximated by

$$N_\sigma(E) = C[\rho_\sigma(E) + \int_{-\psi}^{E} \rho_\sigma(E')D(E-E')dE'] . \tag{1}$$

Here, E is the kinetic energy of the emitted electron, E' is the energy of the excited electron in the metal and may reach the value $-\psi$, where ψ is the metal work function. D(E-E') is the density of probability for a collective excitation to promote an excited electron of energy E' to a secondary electron of energy E (it describes the inverse of the energy loss process). C is an energy dependent proportionality coefficient which contains the physics of the escape mechanism. The polarization P(E) of the secondary electrons is defined by

$$P(E) = \frac{N_+ - N_-}{N_+ + N_-} , \tag{2}$$

Here the subindex +(-) denotes the spin direction of the majority (minority) electrons. The first term on the right hand side of Eq. (1) is dominant and it is found empirically that the total secondary emission[1,5,7], $N(E) = N_+(E) + N_-(E)$, decays almost exponentially with energy[8]. Thus, the approximate relation

$$\frac{\rho_+(E) + \rho_-(E)}{\rho_+(E') + \rho_-(E')} \simeq e^{-\lambda(E-E')} \qquad (3)$$

is used to obtain the following very convenient expression for $P(E)$,

$$P(E) = p(E) + \int_{-\psi}^{E} [p(E') - p(E)]\ e^{\lambda(E-E')} D(E-E')\,dE', \qquad (4)$$

valid up to terms of first order in $D(E)$. Here

$$p(E) = \frac{\rho_+(E) - \rho_-(E)}{\rho_+(E) + \rho_-(E)} \qquad (5)$$

is the smooth structureless polarization of the secondary electrons which, in escaping, were not assisted by inelastic collisions with characteristic excitations of the metal. Notice that in Eq. (4) the coefficient C has cancelled out, making unnecessary any consideration about the details of the escape mechanism in relation to this problem.

A rough numerical estimate for $P(E)$ was obtained as follows. For $E > 0$, the structureless polarization $p(E)$ was approximated by extrapolating the experimental data[1] through the structure (which is almost equivalent to using the theoretical results of Penn et al.[2]). In the region $-\psi < E < 0$ the experimental data were linearly extrapolated (the value $\psi = 5$ eV was used); the results are not very sensitive to the functional form of p(E) in this region as long as p(E) $\overset{\sim}{>}$ 20%. The function p(E) used in the calculation is shown by a dotted line in Fig. 1. From the intensity data of Fig. 2 of Ref. 1, the value λ^{-1}= 5 eV can be derived. Figure 6 of Ref. 5 shows in detail the temperature dependence of the energy loss spectrum of Ni (111) between 100C and 700C. The density of probability D(E) for electron excitation by plasmons was assumed to be proportional to the corresponding energy loss spectrum[9] and, using the above mentioned data, approximated by two peaks, a broad one centered at 19.3 eV (bulk plasmon at 100C) and a sharper one at $\sim$9 eV (surface plasmon) as shown in Fig.1.[10]. The absolute values of D(E) indicated on the scale to the right of the figure, were determined by adjusting the height of the polarization peak to be about 8% as experimentally observed[1]. P(E) obtained evaluating Eq.4 is shown by the full line in Fig. 1. The shoulder extending from about 4 to 10 eV and the peak centered at $\sim$17 eV (with a width of $\sim$5 eV), are in fair agreement with experiment[1].

Surface plasmons are mainly responsible for the shoulder, while the peak is produced by bulk plasmons[11]. Thus, the main peak of the structure must shift to lower energies by about 0.3 eV accompanying the bulk plasmon peak of the energy loss spectrum[5] when the temperature is raised from room temperature to closely below the Curie temperature.

The displacement of about 3-4 eV between the structure of the polarization and the corresponding plasmon excitations indicate that the main contribution to the structure comes from excited electrons from below the vacuum level which, close to the surface , are highly polarized in the direction of the majority spins[2]. Thus, the structure contains information about the polarization of the electrons lying below the vacuum level.

Most probably other characteristic excitations as well, such as single particle excitations which due to band structure effects also manifest themselves in the energy loss spectrum[5], contribute in analogous manner to the polarization spectrum. No attempt, however, was made here to incorporate them.

In sum, the interpretation proposed here for the structure in the spin polarization spectrum of secondary electrons emitted from Ni suggests that, 1) close to the inner surface of Ni, the cloud of excited electrons with energy below the vacuum level is also highly spin polarized (>>5.5%), 2) the principal features of the polarization are induced by the electron-plasmon interaction which assists the emission of those highly polarized electrons providing them with a characteristic energy and, 3) the main peak of the structure (at $\sim$16 eV) must shift to lower energies by about 0.3 eV when the temperature increases from 20 C to closely below the Curie temperature Tc (=360 C). An observation of the shift mentioned in 3) would constitute a crucial test for the model in the sense of an unambiguous identification of the role played by the bulk plasmons.

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FIGURE CAPTIONS

Fig. 1 - Spin polarization of secondary electrons vs. energy. The origin corresponds to the vacuum level. Dotted line: obtained from the experimental data by extrapolating through the structure. Full line: theoretical. The probability D(E) used in the calculations (see text) is also shown with the ordinate scale on the right.

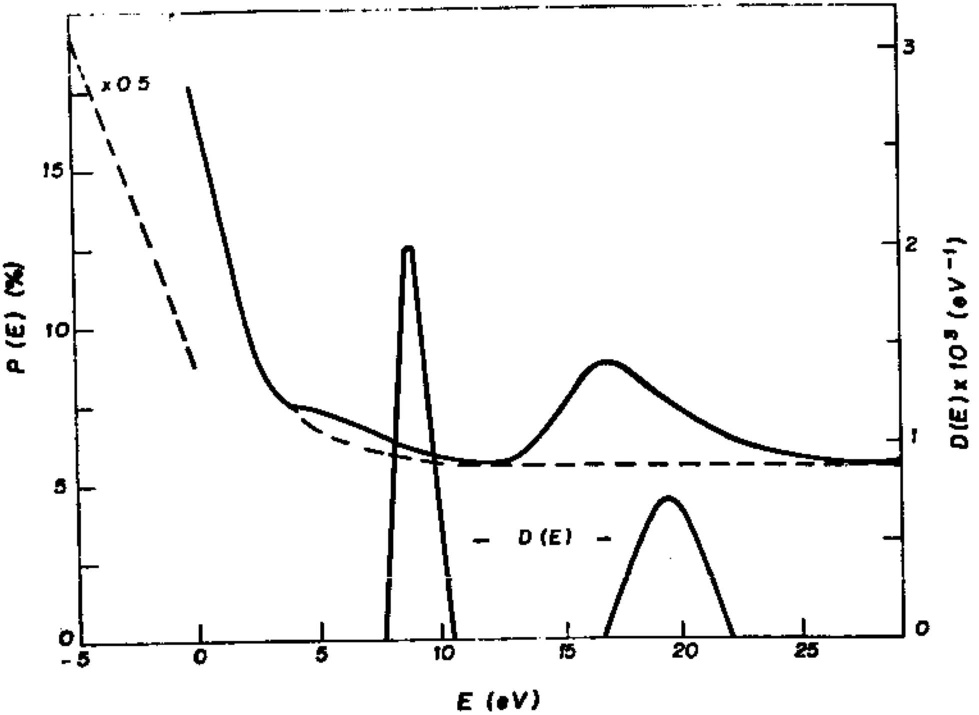

Fig. 1

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[8] As discussed in Ref. 5, the functional dependence of N(E) is more involved. For the purposes of this paper, however, an exponential approximation should suffice.

[9] This assumption essentially implies that the joint density of states and the transition matrix element are slowly varying functions in comparison with the plasmon spectrum.

[10] An accurate calculation would require a proper deconvolution of the energy loss spectrum to isolate the plasmon contribution (see for instance: R.F. Egerton, B.G. Williams and T.G. Sparrow, Proc. R. Soc. Lond. A 398, 395 (1985) and references therein).

The fact that data from the energy loss spectrum of Ni (111) at 100 C are being used to interpret results obtained from Ni (110) at room temperature should not be important in this context because plasma frequencies are not expected to change substantially with the crystalographic direction and within the temperature range 20-100 C.

[11] While the bulk plasmons are responsible for the peak at ∿16 eV, the surface plasmons, whose influence on the energy loss spectrum is more intense, lead only to a shoulder at ∿5 eV. This is a consequence of the exponential factor in the integrand of Eq.(4) which enhances the contribution of the highly polarized low energy electrons as the total emission of the less polarized electrons decreases with the kinetic energy.