It is possible that the broad liquidlike peaks which are indicated by the data at temperatures beyond the line *AB* may be due to such orientationally ordered regions modifed by the periodic potential of the substrate. The Warren line-shape theory used to fit the intensity profiles is in any case not rigorously valid except possibly in the registered solid phase since it does not take into account a continuous decay of particle correlations with distance. More detailed measurements and analysis in terms of various types of pair correlations functions are underway. The details regarding possible critical behavior of both the order parameter and the pair correlations near the transitions are also presently under study. Detailed vapor-pressure–isotherm and specific-heat measurements to verify our proposed phase diagram would be helpful. Quasielastic scattering studies of the diffusion of CH_4 on the graphite surface have also been carried out[15] and further details will be published shortly.

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Theory of Minority-Carrier Injection

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It is shown that minority-carrier injection into trap-free semiconductors at low current densities can lead to a local field maximum and resistance increase. These features disappear at high current densities, and only then is the more familiar expectation of a resistance decrease fulfilled.

As is well known, the transport equations which govern carrier-injection (and all related) processes cannot be solved in analytic form without the introduction of simplifying approximations (e.g., the assumption of space-charge neutrality, the neglect of free-carrier space charges, etc.). The relationships are, however, very complex, and the extent to which these assumptions affect the physics of the situation cannot be safely left to intuitive judgment. In this situation two other approaches are possible: (a) recourse to computer-derived solutions of the complete equations, and (b) linearization of the equation without *ad hoc* assumptions, leading to a "small-signal theory." Approach (b) was described in four previous papers.[1-4] One of the (several) results they yielded was the prediction of a local resistance *increase* as a result of minority-carrier injection

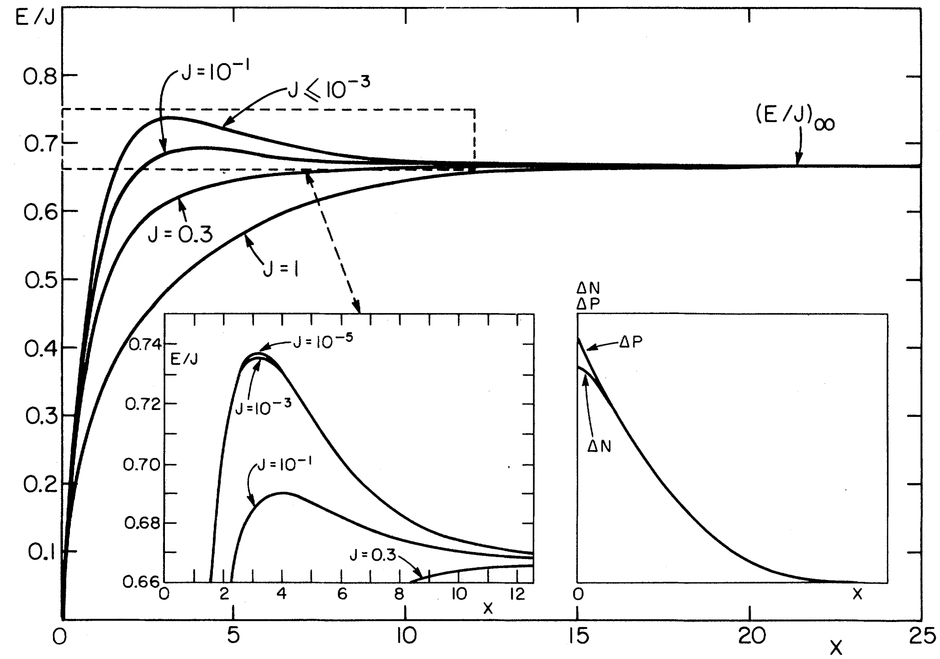

FIG. 1. Computed (field/current) contours for different values of the normalized current density J (see Ref. 1). Unit injection ratio. Other parameters: $b = 2$, $p_e = n_e$, $a = 0.15$ corresponding to intrinsic germanium at $T = 300$ K. Distance x normalized to the Debye length L_D, field E to kT/qL_D, and current J to $\mu_p kT(n_e + p_e)/L_D$. Inset: schematic concentration contours.

into a normal trap-free (lifetime) semiconductor,[5] whereas the popular expectation is a resistance decrease. This expectation is linked historically to the discovery of the transistor, and has since been universally accepted as the only possible result. The linearized equations, analytically solved, suggested in contrast that a different situation must exist at low current densities. The physical argument is easily summarized, e.g., in terms of a contact on n-type material. Holes are injected and decay gradually with distance into the bulk, as shown by the inset in Fig. 1. The condition of space-charge neutrality is almost satisfied over most of this decay region, which means that electrons and holes are subject to equal concentration gradients. Because the two carrier mobilities μ_n and μ_p are *un*equal, identical gradients give rise to unequal and opposed diffusion currents, the electron current being (here) the larger. Under low-current conditions, the local increase in field conductivity due to injected carriers is not itself sufficient to compensate for the electron diffusion current. The compensation, therefore, calls for a locally higher field, implying an increase of *effective* resistivity, in that region. When the conditions are right, this also implies an increase in the *total* resistance of the system. It was clear that this effect would have to disappear at higher current densities when the additional field currents supported by injected carriers *are* large enough to compensate for the "retrodiffusion." However, this conclusion could not be immediately checked, since the linearized solutions were expressly restricted either to low currents,[1,2] or to quasiunperturbed bulk.[3] Computer-derived solutions of the *complete*, unapproximated transport equations were unavailable at the time. To a limited extent, such solutions have recently been obtained, based on Shockley-Read recombination[6] in a semi-infinite system, with an injection plane of injection ratio $\gamma = 1$ at $x = 0$. This means that the current at that plane is assumed to consist entirely of minority carriers. Other injection ratios could have been chosen; the assumption $\gamma = 1$ is by no means critical. Because the calculations are concerned with forward currents, the field is taken as zero at the injection plane. It then increases into the bulk, in accordance with the usual space-charge relationships, to a limiting value of E_∞ that supports the prevailing current in the undistributed meterial at a large distance from the injection plane. The solution of the complete transport equations is then a multi-

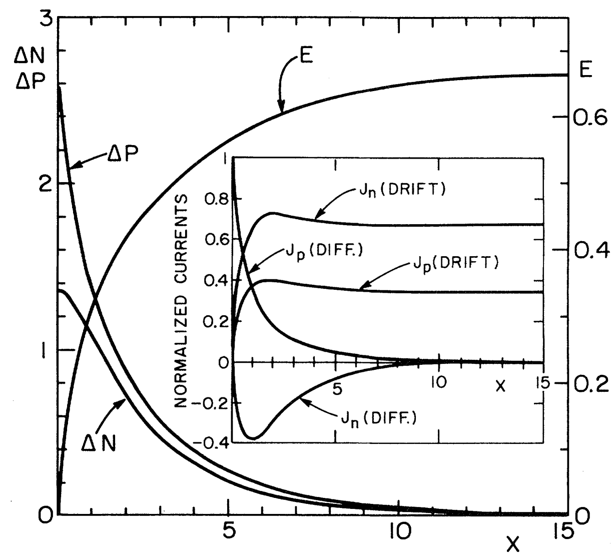

FIG. 2. Computed field and concentration contours for $J = 1$. Parameters as in Fig. 1. Inset: analysis of the transport mechanism; field and diffusion components of J as a function of distance from the injecting interface.

ple-boundary-values problem. Boundary values for the carrier concentrations at $x = 0$ are assumed used in the course of step-by-step calculations based on a Runge-Kutta method, automatically checked for internal consistency, and automatically changed as needed.

The results given below show that previous predictions were correct to a high degree of accuracy, and were in no way peculiarities associated with the linearization process. Figure 1 shows the field contours for four different currents, of which two are associated with local field maxima. Figure 2 gives corresponding concentration and field contours, and an analysis (inset) of the transport mechanism for a total (normalized) current of $J=1$. The field maxima do indeed disappear with increasing current density. This happens when $E_\infty > E_c$, where E_c is given by an analytically derived *estimate*[1]:

$$E_c = \frac{b-1}{b+1}\frac{kT}{q}\frac{1}{L_a} = \frac{b-1}{b+1}\frac{kT}{q}\frac{\mathfrak{a}^{1/2}}{L_D}.$$

Here $b = \mu_n/\mu_p$ is the mobility ratio, L_a is the ambipolar diffusion length, L_D is the Debye length, and $\mathfrak{a}$ (approximately) the ratio of the dielectric relaxation time to the diffusion lifetime.[1] For the example to which Figs. 1 and 2 refer (intrinsic Ge of low carrier lifetime), E_c amounts to ≈ 47 V/cm, corresponding to a value of J in Fig. 1 evidently between 0.1 and 0.3, namely ≈ 0.2. In unnormalized terms, this represents a current density of 10 mA/mm^2. In a material of longer lifetime (other things being equal) the effect would be even more prominent.

Of course, the *total* resistance increase disappears at even lower current densities because it depends on the relative areas above and below the E_∞/J line in Fig. 1. The original experiments of Brattain and Bardeen,[7] which led to the discovery of carrier injection, were carried out at current densities higher than the present limit, which explains why the field maximum was never found.

The effect described is not dependent on traps, and is thereby distinguished from the resistance increase described by Popescu and Henisch.[8] It is also interesting to note that when space-charge neutrality is *a priori* assumed, as is customary, the field is bound to be constant, and the possibility of a field maximum does not then exist. This explains why the field maximum has not featured in previous injection theories related to trap-free material. In practice, and unless special precautions are taken, any increase in *total* resistance arising from minority-carrier injection would tend to be masked by the properties of the contact barrier itself ($x \le 0$), which forms no part of the present analysis.

The effects here discussed are, of course, related to the Dember effect, in as much as both involve gradients of extra carrier concentrations in the same direction. For the Dember effect, an analysis based on the neutrality condition is simple and less misleading because no net current is involved, even though the departures from equilibrium Δn and Δp may be large. In both cases, the effects disappear when $b = 1$.

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Standing Spin Waves Observed by Brillouin Scattering in Amorphous Metallic $Fe_{80}B_{20}$ Films

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We report the first observation of standing spin-wave modes by means of Brillouin light scattering in thin sputtered films of amorphous metallic $Fe_{80}B_{20}$. Results agree with a classical theory and permit determination of spin-wave stiffness $D=(1.4\pm0.2)\times10^{-9}$ Oe cm^2. The value of D is twice as large as that obtained from low-temperature magnetization measurements.

A series of recent experimental and theoretical papers[1-8] have investigated the properties of thermally excited bulk and surface magnons observed by Brillouin scattering from ferromagnetic metals, both polycrystalline and amorphous. Most of this work has been performed on samples which are considerably thicker than the penetration depth of the incident light and hence also than the wavelength of the observed magnons. Here we report on Brillouin scattering from thin films (< 200 nm), in which we have observed for the first time a substructure in the bulk magnon scattering. We perform our experiments on amorphous sputtered films of $Fe_{80}B_{20}$.

It is well known that a bulk magnon of wave vector $\vec{q}$ propagating perpendicular to an applied magnetic field $\vec{H}$ has a frequency ν given by[9,10]

$$2\pi\nu=\gamma[(H+Dq^2)(H+4\pi M+Dq^2)]^{1/2}, \qquad (1)$$

where γ is the gyromagnetic ratio, M the magnetization of the sample, and D the spin-wave stiffness. In a thin film with either complete pinning or no pinning at the surface, the wave-vector component q_x perpendicular to the film is quantized according to $q_x=n\pi/L$, where L is the sample thickness and n is an integer. For the case of no pinning, $n=0, 1, \ldots$; when pinning is present, $n=1, 2, \ldots$. Clearly, the smaller the thickness, the larger the separation between the different modes. In thicker samples which have been studied earlier by light scattering,[1-3,8] the separations were smaller than experimental resolution, and only a single broad and asymmetric peak was observed.

The fact that our samples are metals rather than insulators has a negligible effect on the mode positions of Eq. (1), for given the resistivity of our amorphous materials of roughly 200 $\mu\Omega$ cm, the skin depth is over ten times the thickness of even our thickest film throughout the investigated frequency range. However, we expect the large absorption coefficient of the metal to affect the light-scattering selection rules. In conventional scattering studies of transparent materials, there is a selection rule based on wave-vector conservation between incident and scattered light and the excitation itself. However, as recently shown,[2,4,8] the large absorption coefficient effectively leads to a spreading inside the metal, of the light's wave-vector component perpendicular to the surface. Therefore, for a given scattering geometry one can simultaneously scatter from a series of spin waves with different values of q_x.

The Brillouin spectra were taken with a five-pass Fabry-Perot interferometer. Thin samples of varying thicknesses of amorphous $Fe_{80}B_{20}$, deposited by sputtering on silicon substrates,[8,11,12]

