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Temperature-dependent plasmons in InSb

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Abstract. The temperature dependence of the conduction-band plasmon excitation in doped InSb has been measured by high-resolution electron energy loss spectroscopy (HREELS). Previous measurements, carried out at 300 K, have shown that preparation of the (100) surface of p-type InSb, by low-energy ion bombardment and annealing, leads to a near-surface region having a so-called depletion layer of approximately 200 Å caused by Fermi level pinning at the surface. Below this, an n-type layer extends a further 500 Å into the material arising because of the ion-induced damage. Measurements of the plasmon energy reported here indicate an asymmetric broadening giving rise to an apparent shift of about 7 meV to lower energy as the surface temperature is raised from about 200–470 K. More significant is a large increase in the intensity of the plasmon between 300 and 470 K. By using model calculations, based on dielectric theory, we interpret these results in terms of an increased contribution to the conduction-band free-carrier concentration leading to a reduction in the thickness of the depletion layer.

1. Introduction

The observation of conduction-band plasmon excitations in semiconductor materials by high-resolution electron energy loss spectroscopy (HREELS) has proved significant in the understanding of important surface and interfacial properties such as band bending and Fermi level pinning (for examples see [1] and references therein). These effects are fundamental in achieving a full appreciation of the overall electronic properties of semiconductor materials and devices.

Although the electronic properties of semiconductor surfaces have been studied extensively, the effects of surface temperature on the behaviour of these materials has received relatively little attention. Two recent HREELS studies, on Si(111) [2–4] and GaAs(100) [5], have addressed this problem but have focused on the broadening of the quasi-elastic peak as a function of increasing temperature. This broadening effect has been explained in terms of the increasing thermal excitation of free carriers into the conduction band across the band gap. The model proposed also accounts for band bending and Fermi level pinning due to the existence of surface states.

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The consequence of band bending has, in general, been well documented for III–IV semiconductor surfaces at room temperature [6]. An additional complexity is, however, introduced for narrow band gap materials such as InSb, by this very property of the material and its effect on the degree of band bending observed. In a series of recent publications we have shown that the degree of band bending is extremely sensitive to the details of the surface preparation [7–9]. Measurements of the plasmon energy as a function of the kinetic energy of the incident electrons, for surfaces prepared by ion bombardment and annealing, leads to the formation of a highly inhomogeneous free-carrier profile in the near-surface region (typically < 1000 Å) [8]. The effects of this on low-doped p-type InSb(100) was to produce a region of material exhibiting n-type behaviour. This layer was sandwiched between the bulk p-type material and a depletion layer arising from Fermi level pinning close to the valence band maximum by surface states, effectively forming a p–n–p junction (see figure 1) [9].

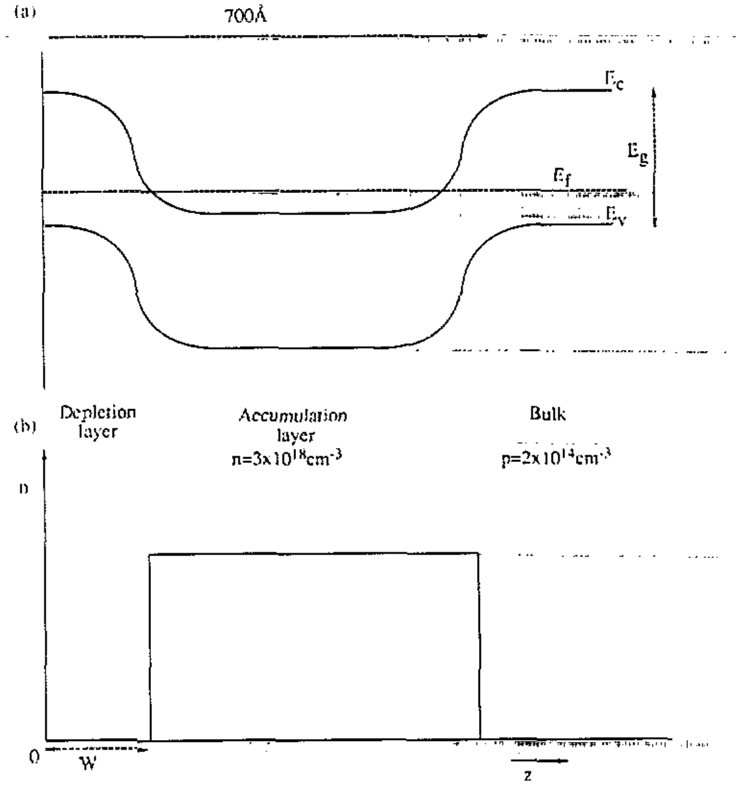

Figure 1. The (*a*) band bending and (*b*) corresponding free-carrier profile obtained from energy-dependent HREEL spectra for a p-type InSb(100) sample ($p \simeq 2 \times 10^{14}$ cm^{-3}) following ion bombardment and annealing (see [9]).

In this paper, measurements of the energy and intensity of the plasmon are presented as a function of surface temperature for p-type InSb(100) (about 2×10^{14} cm^{-3}) prepared by ion bombardment and annealing.

2. Experimental details

Experiments were performed in an ultra-high-vacuum chamber with a base pressure of approximately 5×10^{-11} mbar (VSW Scientific Instruments, UK). Surface characterization was achieved by low-energy electron diffraction (LEED) and Auger electron spectroscopy. Specular HREELS measurements, at a primary energy of 30 eV, were made on p-type (around 2×10^{14} cm^{-3}) InSb(100) prepared by argon ion bombardment (500 eV ions) and annealing (up to 600 K). A more detailed description of the surface preparation and HREELS experiments has already been published [8].

3. Results and discussion

Figure 2 shows a series of HREEL spectra, recorded at different surface temperatures, on the p-type InSb(100) surface. At 300 K the conduction-band plasmon is observed at a loss energy of 45 meV. The corresponding gain peak can also be seen but with a significantly reduced intensity dictated by the Boltzmann factor. Changing the temperature of the sample results in an asymmetric broadening of the plasmon peak giving rise to an effective decrease in the plasmon energy from 50 meV at 200 K to 43 meV at 470 K. More significant with regard to this paper is the major change in the intensity of the plasmon loss with temperature. At 200 K, there is a slight reduction in the intensity of the loss peak (*ca* 10%). In contrast, at elevated temperatures (470 K), the intensity of the loss feature is significantly increased (> 100%) with respect to the room temperature data. There is also a corresponding greater increase in the intensity of the gain peak as the temperature is raised because of the increased population of the excited plasmon level.

HREELS has been used (both by ourselves [7–9] and others [1, 10, 11]) to monitor the energy and intensity of the plasmon loss of a variety of semiconductors as a function of incident electron energy (E_0), allowing the depth of the depletion layer caused by surface Fermi level pinning to be determined. The incident electron is non-intrusive but couples to the plasmon at progressively greater depths with increasing E_0 [12]. For the case of a depletion layer, the intensity of the plasmon (generally described as an interface plasmon between the depletion layer with no free carriers and the undepleted bulk [11]) is weak at low-electron energies but increases with E_0. The maximum in the plasmon intensity and its position (in E_0) depends on the depletion layer thickness, which is itself dependent on the bulk doping level and the dielectric constant of the material. In the case of this ion-bombarded p-type InSb, we have determined the thickness of the depletion layer to be about 200 Å [9]. There is, however, an added complication for this narrow gap material. Ion bombardment produces an accumulation layer (about 3×10^{18} cm^{-3}) some 500 Å thick below the depletion layer and results in the formation of a p–n–p junction (figure 1) [9]. We have interpreted the accumulation as arising from ion-induced Sb vacancies acting as donors.

The large increase in plasmon intensity, which is observed in figure 2, indicates that, for a given sampling depth (i.e. a fixed E_0 of 30 eV), there is a stronger coupling between the incident electron and the interface plasmon as the temperature of the substrate is increased. Model calculations have been carried out using the method of Lambin *et al* [13]. These involve a dielectric approximation to characterize the response of the material to the long-range Coulomb field of the incident electrons enabling the plasmon intensity and energy to be determined, both as a function of depletion layer thickness and incident electron energy. Preliminary results are shown in figure 3 for the free-carrier profile shown in figure 1(*b*) using two different thicknesses

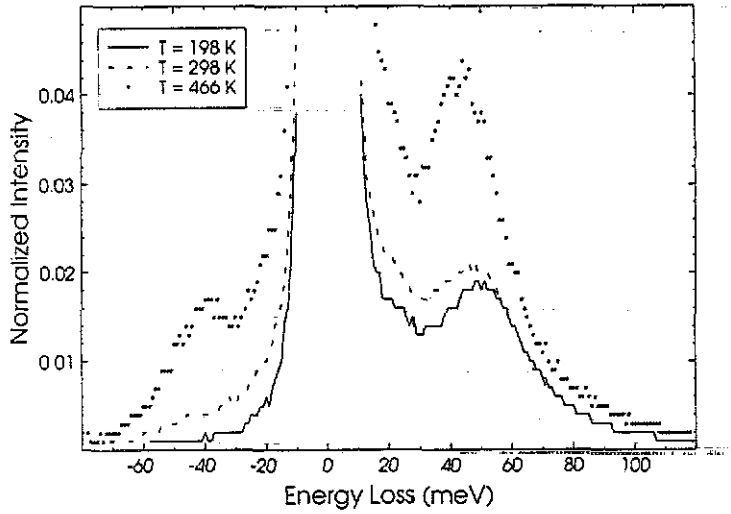

Figure 2. Specular HREEL spectra from an InSb(100) p-type sample ($p \simeq 2 \times 10^{14}$ cm^{-3}) at $E_0 = 30$ eV for three different substrate temperatures. These spectra clearly show an increase in the intensity of the conduction-band plasmon over the temperature range $T = 200$–470 K.

for the depletion layer (W). The changes in the intensity of the plasmon observed in the HREELS experiments between 300 and 470 K are essentially reproduced by a reduction in the depletion layer thickness of a factor of two. Although our model accounts for the intensity changes, the calculations indicate an *upward* shift in the plasmon energy with increasing substrate temperature. This is at variance with our experimental data which shows an apparent 3–4 meV shift to lower energy between 300 and 470 K. As yet we have no explanation for this discrepancy and further calculations are under way to address this problem.

The physical explanation for the reduction in depletion layer thickness is as yet unclear. We can eliminate the possibility that this is a consequence of the increased contribution to the conduction-band free-carrier concentration from intrinsic excitations. In a standard two-layer model (i.e. depletion/bulk), the depletion layer thickness, d, is related to the band bending, V_{bb}, by $d^2 = 2\epsilon_0\epsilon(0)V_{\mathrm{bb}}/ne$, where n is the bulk donor concentration, ϵ_0 is the permittivity of free space and $\epsilon(0)$ is the static dielectric constant. For the InSb used in our measurements we take $n \simeq 3 \times 10^{18}$ cm^{-3} (i.e. the acculmulation layer). If we assume that V_{bb} is constant (almost certainly an oversimplification) the increase in the intrinsic free-carrier concentration from 2×10^{16} cm^{-3} at 300 K to 6×10^{16} cm^{-3} at 470 K clearly results in a negligible change in the depletion layer thickness.

A more likely explanation for the observed temperature dependence is that deep levels, arising from the ion bombardment process, act as donor states and are ionized as the substrate temperature is raised. This would result in an increase in the number of free carriers occupying the conduction band and also cause a change in the degree of band bending and a subsequent reduction in the thickness of the depletion layer. By performing more extensive measurements and calculations on InSb samples with different bulk doping levels, both as a function of E_0 and temperature, we hope to be able to determine the origin of the increased carrier concentration in the near-surface region, which accompanies the rise in temperature.

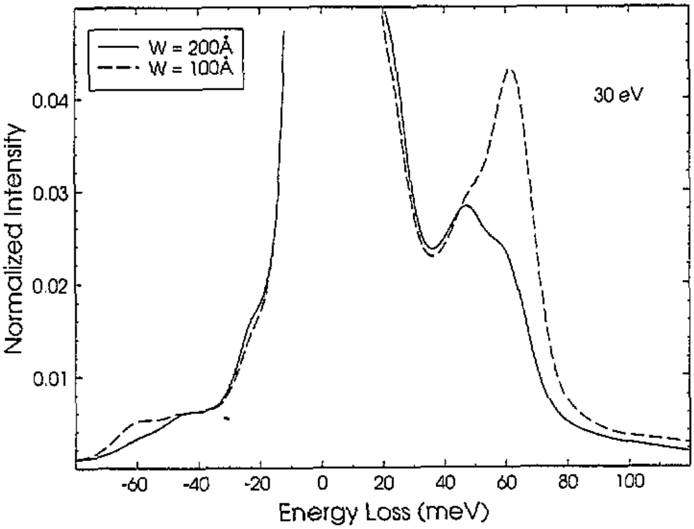

Figure 3. Calculated HREEL spectra, based on a dielectric approximation, for InSb(100) using the p–n–p profile shown in figure 1(*b*). The free-carrier concentration in the accumulation layer was 3×10^{18} cm^{-3} and the depletion layer thickness, W, was varied between 200 and 100 Å. The spectra were calculated for incident electrons of 30 eV.

4. Conclusions

HREELS has been used to monitor the temperature dependence of plasmon excitations in ion-bombarded p-type InSb. Although a small decrease in the plasmon energy (7 meV) is observed with increasing temperature (between 200 and 470 K), the most significant change is a large increase in the intensity of the plasmon loss arising from an increase in the number of free carriers occupying the conduction band. This observation cannot be explained simply by an increased intrinsic contribution of the narrow gap semiconductor, but must arise from a reduction in the thickness of the depletion layer. Model calculations suggest that the depletion layer thickness is reduced by a factor of two as the temperature of the InSb is raised from 300 to 470 K. Further experiments and calculations are required in order to determine the essential physics of this important temperature dependent effect. Such work may be of great interest in understanding the device capabilities of these complex materials.

Acknowledgments

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