Magnetic-field dependence of PbTe-EuTe transistor characteristics

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Lead telluride insulated-gate field-effect transistors have been fabricated from epitaxial films with electron densities of 10^{13} cm^{-3}, and their transport properties have been determined in fields up to 18 T. Switching (on-off) ratios up to 10^4 have been attained at 1.2 K. The carrier density is a strong function of magnetic field when gate bias is applied, leading to a very large magnetoresistance effect. In particular, at a threshold value of the magnetic field, a thousandfold increase in resistance and Hall coefficient are observed at 4.2 K. A PbTe/EuTe superlattice between the PbTe channel and the (111) BaF_2 substrate surface was present in these devices in order to obtain low carrier densities in the PbTe channel region.

INTRODUCTION

The experimental quest for Wigner condensation in low-carrier-density narrow-gap semiconductors has led to some interesting debate,[1,2] centered around the question of whether the observed metal-semiconductor transitions in n-type $Hg_{1-x}Cd_xTe$ ($x \simeq 0.2$) is a magnetic freeze-out or a genuine electronic phase transition. In IV-VI compounds, and particularly PbTe where the dielectric constant is of the order of 400 –1000, the impurity binding energies are in the $10^{-6}-10^{-7}$-eV range. One would therefore expect that the transport properties in the liquid-He^4 range and high magnetic fields are less influenced by interactions of electrons with impurities than they are in other narrow-gap semiconductors, although the electron-electron interactions should be similarly reduced by the high dielectric constant. In the present work, we focus on thin (1000-Å) epitaxial PbTe films in which we achieved, to our knowledge for the first time, electrons densities as low as 10^{13} cm^{-3} at 4.2 K. We used a gate electrode to be able to vary the electron density at will during our high-field transport measurements. The results we describe here show that we have field-induced carrier freeze-out even at 4.2 K, a temperature too high for electron-electron interactions to dominate.

Lead telluride transistors have previously been fabricated in thin-film form on glass,[3] NaCl,[4] and BaF_2 (Refs. 5 and 6) substrates. They are potentially useful for signal processing in integrated infrared detectors because of their narrow energy band gap, $E_g = 0.2$ eV at low temperatures.[7] PbTe has an electron mobility of 1500 cm^2/V sec at room temperature and 15 000 cm^2/V sec at 77 K, even at large electron concentrations of 10^{19} cm^{-3}.[8] $Pb_{1-x}Eu_xTe$ is the preferred semiconductor to make infrared ($\lambda > 2.7$ μm) diode lasers.[9] Since there is no other conduction-band minimum at energies less than 0.6–1.0 eV above the one at the L-point of the Brillouin zone,[7] a value larger than the direct L-point energy gap, non-parabolicity dominates the electron band structure. In the pure two-band model, the group velocity of hot electrons at energies $E > E_g$ saturates at

$$v_g = \frac{1}{\hbar}\frac{dE}{dk} = \left[\frac{E_g}{2m^*}\right]^{1/2} .$$

Therefore, $v_g \geq 2 \times 10^9$ cm/sec in the plane perpendicular to the $\langle 111 \rangle$ axis, i.e., close to the speed of light in the material. These factors make PbTe potentially useful as a semiconductor for the base region of a hot-electron transistor. Holes also fill bands at the L points of the Brillouin zone, somewhat symmetric to the electron bands, though a heavy-hole band exists at the Σ point, 0.19 eV below the L-point maximum.[10]

EXPERIMENT

In this study, insulated-gate field-effect transistors were fabricated with a PbTe channel layer on an insulating BaF_2 substrate. The substrates were cleaved in air along the $\langle 111 \rangle$ orientation and immediately inserted into the load lock of a Physical Electronics Model 400 molecular-beam epitaxy (MBE) system. After heating the substrates to the growth temperature (typically 300 °C), PbTe was deposited from a single source oven at 1 μm/h in a vacuum of 1×10^{-9} Torr (10^{-7} Pa). It was desirable to obtain low carrier densities for the present devices, and since vacancies effectively dope PbTe, the stoichiometry of the films was adjusted by adding Te from a second source oven. However, the carrier densities, measured by the Van der Pauw technique on 2-μm-thick films, were always $(1-5) \times 10^{17}$ cm^{-3} [areal density of $(2-10) \times 10^{13}$ cm^{-2}] over a wide range of growth temperatures (300–400 °C), substrate prebaking conditions, and Te flux during growth. Annealing the films after growth in sealed, evacuated quartz ampoules gave somewhat lower carrier densities (5×10^{16} cm^{-3} or 1×10^{13} cm^{-2}). Decreasing the film thickness to 0.1 μm gave films which invariably had hole concentrations of $(2–3) \times 10^{18}$ cm^{-3} [or $(2–3) \times 10^{13}$ cm^{-2}]. Since the dielectric constant of PbTe varies from 400 at room temperature to over 1000 at low temperatures,[7] the depletion widths of these latter films were comparable to their thickness. Thus, the exact significance of carrier concentration measurements on such films is open to question. Nevertheless, the constancy of the areal densities suggests that much of the difficulty in obtaining low carrier densities in these films is caused by a large acceptor concentration at the PbTe/BaF$_2$ interface. This may be related to the 4% lattice mismatch between PbTe ($a=6.460$ Å) and BaF$_2$ ($a=6.200$ Å) and the large dislocation density observed[11] at that interface.

These results led us to interpose a PbTe/EuTe [(15 Å)/(15 Å)] superlattice buffer layer of 15 periods between a PbTe nucleation layer (500 Å thick) and the final PbTe channel layer (1000 Å thick). This superlattice was intended to electrically isolate the PbTe channel from the substrate interface. A similar superlattice was grown[12] (in order to study its magnetic properties) without the top 1000 Å of PbTe, and was electrically insulating. The lattice constant of bulk EuTe (6.585 Å) is about 2% higher than that of PbTe (6.460 Å, Ref. 5), but TEM analysis of this structure indicated that the layers grew essentially dislocation-free. The layers in the PbTe/EuTe superlattice were 15 Å thick, very much thinner than the critical thickness above which strained layers of that system should relax their elastic energy in dislocations.

A six-terminal Hall effect pattern was etched into the multilayer structure, and shallow contacts were made to the top 1000 Å of PbTe. The width of the Hall bar was 50 μm, the length between the resistance measurement contacts was 200 μm. The whole structure was then equipped with a gate: a 5000-Å layer of polymethylmethacrylate (PMMA) photoresist and a gold gate electrode. Measurement currents up to 100 nA (at liquid-He temperatures) or 10 μA (at room temperature) were used. At zero gate bias, where the transistor is off, we took I-V characteristics at 4.2 K for currents from 10^{-11} to 1.5×10^{-8} A and at room temperature for currents from 10^{-9} to 10^{-5} A. In order to have reasonably accurate measurements when the transistor is on, we then chose the measurement current as high as possible, but still such that the I-V characteristic was linear to better than 5%. Gate voltages were limited from -30 to $+30$ V. The variation of the resistance at low temperature as a function of gate voltage is shown in Figure 1. The ratio of the resistance of the plateau from $V_G=0$ V to the resistance for $V_G=30$ V is 10^4 at 1.2 K, but drops as the temperature is increased. We show that as $(R_{\text{off}}-R_{\text{on}})/R_{\text{on}}$ in Fig. 2. We explain the temperature dependence of this quantity by the fact that it is sensitive to both the number of capacitively coupled electrons in the channel, and the number of residual free electrons present in the PbTe film. From the capacitance formula, one can calculate that at $V_G=30$ V the areal density of free electrons is 8.3×10^{11} cm^{-2}, independent of temperature. Hall measurements made with $V_G=0$ show that the residual electron concentration is a strong function of temperature: the areal electron density N_S is also shown in Fig. 2. This measurement was repeated on six samples, with polyimide as well as PMMA gate insulators. Since the depletion width at low temperature is of the order of the film thickness (1000 Å), the samples have low-temperature electron densities of as little as 10^{13} cm^{-3}, a record for PbTe to our knowledge. The temperature dependence of N_S suggests an activated behavior, with a binding energy of about 20 meV. We speculate that this is due to a deep level. In view of the large dielectric constant of PbTe ($E_r=400$–1500), the effective Rydberg binding energy of an impurity level is normally of the order of 10^{-6}–10^{-7} eV, and deep levels in PbTe are not usually observed. Hence we suspect that a deep level is associated with the presence of the PbTe/EuTe superlattice.

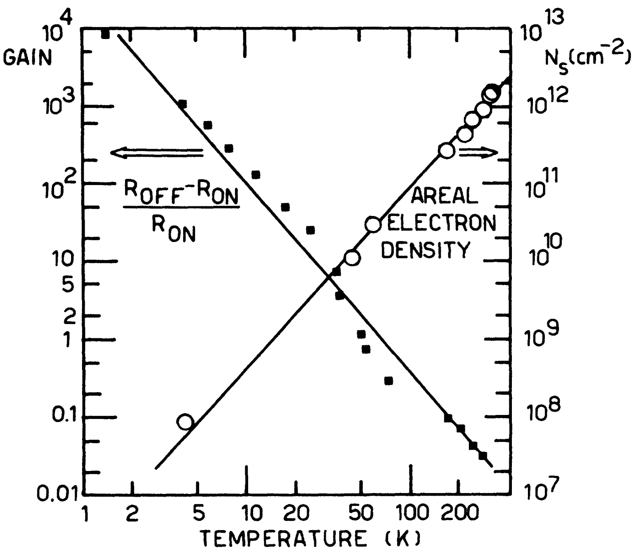

FIG. 1. Temperature dependence of the areal electron density N_S (right ordinate) at $V_G=0$, and of the relative ratio of the resistance at $V_G=0$ to that at $V_G=30$ V (left ordinate).

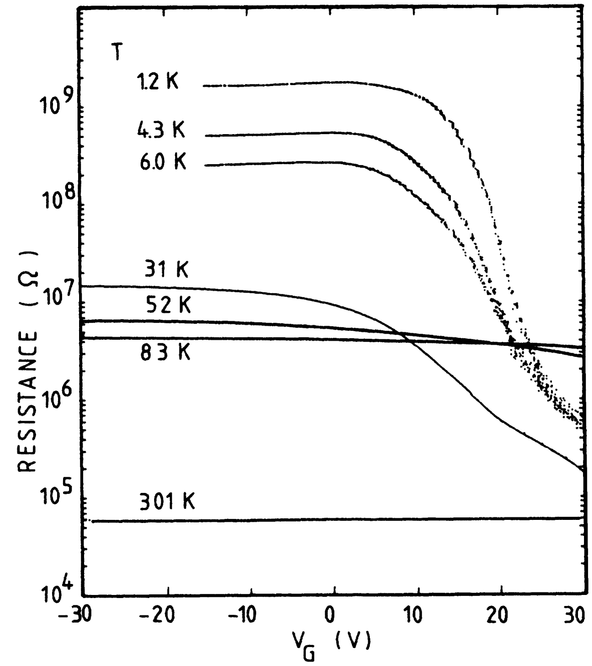

FIG. 2. Resistance variation of the sample, 200 μm long and 50 μm $\times$ 0.1 μm thick, as a function of gate bias V_G.

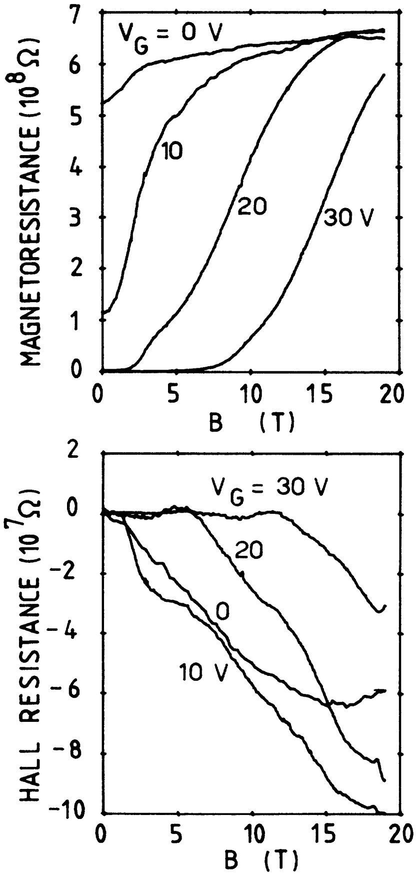

FIG. 3. Magnetic-field dependence, at 4.3 K, of the Hall resistance and the magnetoresistance for various values of the gate bias voltage V_G.

In order to explore the magnetic field dependence of this deep-level binding energy, we measured the low-temperature (4.3–17-K) field dependence of the Hall effect and magnetoresistance up to 19 T. Selected results are shown in Fig. 3. For zero gate bias we measure an almost linear Hall resistance, which corresponds to the areal density shown in Fig. 2. The magnetoresistance also behaves normally: a B^2 law at low field, followed by a saturation. When $V_G \geq 20$ V, at low field, an appreciable electron concentration is present and the Hall resistance is low—and difficult to measure from Fig. 3 because the sample current was 1 nA. However, at a critical field B_C, the Hall resistance increases strongly and resumes the slope it had for $V_G = 0$. Similarly, the magnetoresistance which was low for $V_G > 20$ V and $B < B_C$ increases, and saturates at the same value as for $V_G = 0$. This suggests that the deep level that is responsible for the freeze-out of the electrons with decreasing temperature has a strongly magnetic-field-dependent binding energy. To illustrate this, we can obtain the values of the critical field B_C from the magnetoresistance curves by taking the tangent at the inflection point of the curve, and defining B_C as the intercept of that tangent with the abscissa. In Fig. 4, we plot B_C as a function of the areal density N_S which we calculate from the capacitance formula and the applied gate voltage V_G. Figure 4 hence represents a magnetic-field-dependent density of electron trapping states, suggesting that they could be associated with the presence of magnetic Eu ions. Another possibility which could lead to device applications would involve a field-dependent depletion layer in the 1000-Å active region, which could arise from a field-dependent band offset between the active region and the EuTe/PbTe superlattice.

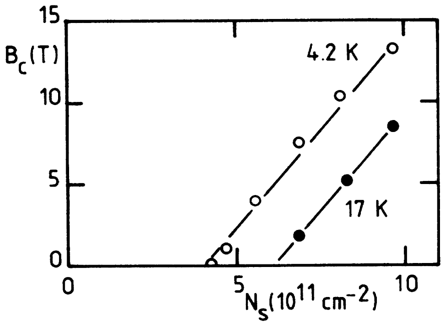

FIG. 4. The critical magnetic field B_C for two temperatures (4.2 and 17 K) as a function of the areal electron density N_S deduced from the applied gate bias V_G. At $B > B_C$, the capacititvely induced electrons are frozen out.

CONCLUSIONS

In summary, we have described in this paper an insulated-gate field-effect transistor made in epitaxial PbTe grown on a PbTe/EuTe superlattice. This epitaxial PbTe has the lowest carrier concentrations reported at 4.2 K in PbTe, equivalent to 10^{13} cm^{-3}, presumably because of the presence of a deep trap. The binding energy of this trap shows strong sensitivity to the applied magnetic field. We can only speculate about the nature of the trap. It seems probable that the presence of a magnetic-field-sensitive energy level related to the Eu ions in the superlattice, or a magnetic-field-dependent band offset between the EuTe/PbTe superlattice and PbTe is the physical mechanism underlying our observation.

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