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Polarization dependence of the electroabsorption in low-temperature grown GaAs for above band-gap energies

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We have measured the electroabsorption in low-temperature grown GaAs by performing room-temperature transmission experiments in the spectral range from 1.3 to 1.9 eV for different electric fields induced by a voltage applied to a metal-semiconductor-metal structure. The devices were separated from the substrate by using an epitaxial liftoff technique. Therefore, we have been able to observe the electro-optic effect at the fundamental band gap as well as at the split-off band edge. The absorption is clearly polarization dependent at the fundamental band gap but only weakly at the split-off band gap, in agreement with the theory of the Franz–Keldysh effect. © *1996 American Institute of Physics.* [S0003-6951(96)00721-8]

GaAs grown by molecular beam epitaxy (MBE) at low substrate temperatures from 190 to 300 °C [low-temperature grown (LT-)GaAs] is known as a material with unique optical and electrical properties.[1,2] After annealing it exhibits a high specific resistance[3] of up to 10^7 Ω cm, strongly enhanced dielectric breakdown fields[4] as large as 5×10^5 V/cm and extremely short lifetimes of photoexcited carriers[5,6] (<1 ps). These properties make LT-GaAs very appealing as a material for a large number of applications[7,8] like fast photodetectors, optical switches, or electro-optic moldulator structures.

In this letter, we present fundamental investigations of the Franz–Keldysh effect (FKE) in LT-GaAs. Previous investigations have shown that the absorption changes are comparable with the FKE in GaAs grown at high temperatures, despite a significantly broader width of the first Franz–Keldysh oscillation.[9] To observe the FKE we performed transmission measurements on metal-semiconductor-metal (MSM) structures. These structures have the advantage that they can be processed very easily even with small finger spacing. Therefore small applied voltages may induce quite large lateral electric fields. In addition the in-plane orientation of the electric field in MSM structures in combination with the epitaxial liftoff technique allows polarization dependent transmission measurements even for photon energies far above the band gap.

Our samples consist of a 50 nm AlAs sacrificial layer grown at 580 °C on a semi-insulating GaAs substrate followed by 1.3 μm undoped LT-GaAs grown at 250 °C. The growth rates were about 0.3 μm/h for AlAs and 0.7 μm/h for the LT-GaAs. During the entire growth process the As_4 flux was kept constant and the III/V beam equivalent pressure ratio was 1/13. X-ray diffraction measurements showed that the samples have a good crystalline quality.

After growth the samples were annealed in a rapid thermal annealer at 600 °C for 1 min in N_2 atmosphere, lying upside down on a GaAs substrate to avoid the evaporation of As. The annealing procedure renders LT-GaAs semi-insulating.[3] Afterwards Ti/Au Schottky contacts and finally a SiO antireflection coating were evaporated on the surface of the samples. The interdigitated finger contacts had a width of 1 μm and a spacing varying between 1 and 14 μm. The total device area was 100 μm×100 μm. To perform transmission measurements at photon energies far above the band gap, the LT-GaAs layer was separated from the substrate using an epitaxial liftoff technique.[10]

Before and after the epitaxial liftoff the $I-V$ characteristics of the devices were nearly identical, indicating that the liftoff process does not influence the electrical properties of the LT layer. Due to the high resistance of annealed LT-GaAs we obtained very low dark currents, e.g., 2 μA at 40 V for 3 μm finger spacing. The photocurrents were also very low because of the extremely short lifetimes of photoexcited carriers in LT-GaAs. Therefore, MSM structures on LT-GaAs enable ''low current'' investigations of the electroabsorption even for high electric fields. The same investigations at MSM structures on epitaxial layers of standard GaAs fail because of strong thermal effects due to high dark and photocurrents. Note, that the samples were separated from the substrate which normally acts as a heat sink.

For the investigation of the FKE we measured the transmission as a function of photon energy for various applied voltages across the metal contacts. We illuminated the samples with a 250 W tungsten lamp via a monochromator and an optical fiber. Figure 1 shows the absorption changes of a MSM structure with an applied voltage of 40 V with respect to the 0 V absorption. Below the band gap at 1.42 eV the well-known Franz–Keldysh absorption is observed, whereas above the band gap three Franz–Keldysh oscillation extrema occur between 1.42 and 1.6 eV. The amplitude of the oscillations is decreasing very fast, probably due to an inhomogeneous electric field in the MSM structure.

A similar structure with an amplitude which is about one order of magnitude smaller, is observable at photon energies

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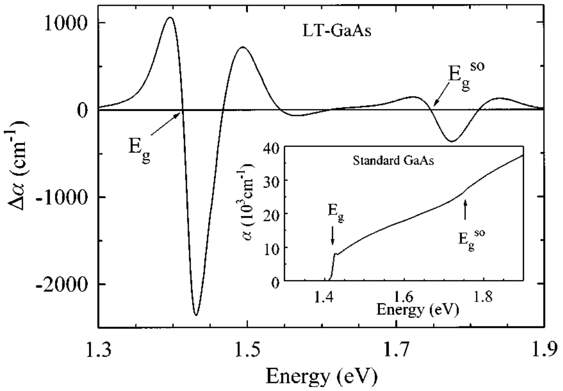

FIG. 1. Electroabsorption of unpolarized light in LT-GaAs for an applied voltage of 40 V and a fingerspacing of 3 μm. Note the FKE at the fundamental band gap and the split-off band gap. The inset shows the 0 V absorption spectrum of standard GaAs. The fundamental band gap and the split-off band edge are indicated by arrows.

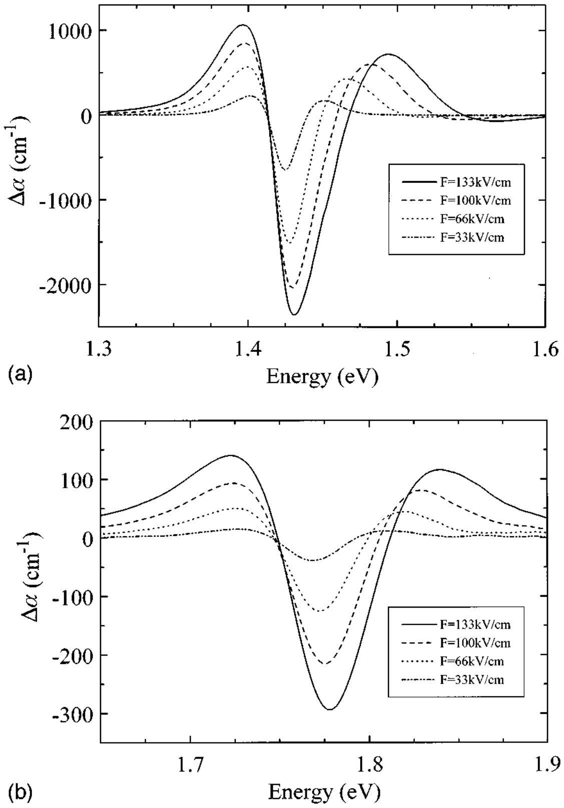

FIG. 2. (a) Electroabsorption of unpolarized light near the fundamental band gap of LT-GaAs for applied voltages of 10, 20, 30, and 40 V. (b) Electroabsorption of unpolarized light near the split-off band gap of LT-GaAs for applied voltages of 10, 20, 30, and 40 V.

0.34 eV above the fundamental band gap of GaAs. It results from transitions between the spin split-off valence band and the conduction band, which additionally contribute to the absorption of GaAs for photon energies higher than 1.76 eV. This interpretation is supported by the fact that the energetic position of this structure coincides with the spin split-off band-gap E_g^{so} observed in the 0 V absorption spectrum of standard GaAs shown as an inset of Fig. 1 as well as in the 0 V absorption spectrum of annealed LT-GaAs.[11] As the split-off band absorption is also influenced by an applied electric field the FKE appears at E_g^{so}, as well. Note, that the FKE at E_g^{so} is only observable because of the strong decrease of the Franz–Keldysh oscillations at the fundamental band gap.

Figure 2(a) shows the field induced absorption changes near the energy of the fundamental band gap for four different electric fields (33, 66, 100, 133 kV/cm). The maximum absorption change is about 2300 cm^{-1} for an electric field of 133 kV/cm. This is comparable to the electroabsorption in standard GaAs. The values for the electric fields represent estimates obtained by dividing the applied voltage by the finger spacing. Numerical calculations show that the actual electric fields in the LT-GaAs are nonuniform and smaller than the above approximations for the main part of the active device area.

The FKE at the split-off band can be seen in Fig. 2(b). At these energies the maximum field induced absorption changes were about 300 cm^{-1} for $E=133$ kV/cm which is almost one order of magnitude lower than the absorption changes at the fundamental band gap.

As mentioned in the introduction a particularly appealing feature of our structure is the possibility to investigate polarization effects of the electroabsorption. Figure 3(a) shows a logarithmic plot of the absolute values of the field induced absorption changes in the LT-GaAs layer for photon energies near the fundamental band gap and for both, transverse electric (TE) and transverse magnetic (TM) polarization of the light. (By definition the electric field vector of the incident light wave is perpendicular to the field vector of the applied electric field for TE polarized light and parallel to it for TM polarized light.) The strong dips in the spectrum are due to the zero crossings of the absorption changes. A clear difference of the absorption changes between TE and TM polarized light is evident. Below the band-gap energy the TM absorption is higher than the TE absorption. Above the band gap the Franz–Keldysh oscillations of the TE polarized light show shorter oscillation periods compared with those of TM polarized light.

For photon energies around the split-off valence band to conduction band transition (at 1.76 eV) we observed no significant polarization dependence of the Franz–Keldysh oscillations. Figure 3(b) shows a logarithmic plot of these absorption changes for both polarizations and the same electric fields as before. For photon energies around 1.8 eV the minima of the absorption changes are at the same wavelength for both kinds of polarization within our accuracy of measurement. The small polarization dependence of the minima at the split-off gap and the deviates in the low energy range are due to the influence of the FKE at the fundamental band gap.

The experimental results can be discussed within an effective mass approximation using anisotropic momentum matrix elements.[12] This theory can be shown to give correct results for photon energies below the band gap,[13] and it is also appropriate for a qualitative discussion of the Franz–Keldysh oscillations and their polarization dependence for energies above the band gap. However, an exact description of the FKE above the band gap can be given only by employing a $\mathbf{k}\cdot\mathbf{p}$ model.[14]

In the EMA the absorption α is proportional to the sum of three terms corresponding to the contributions of the dif-

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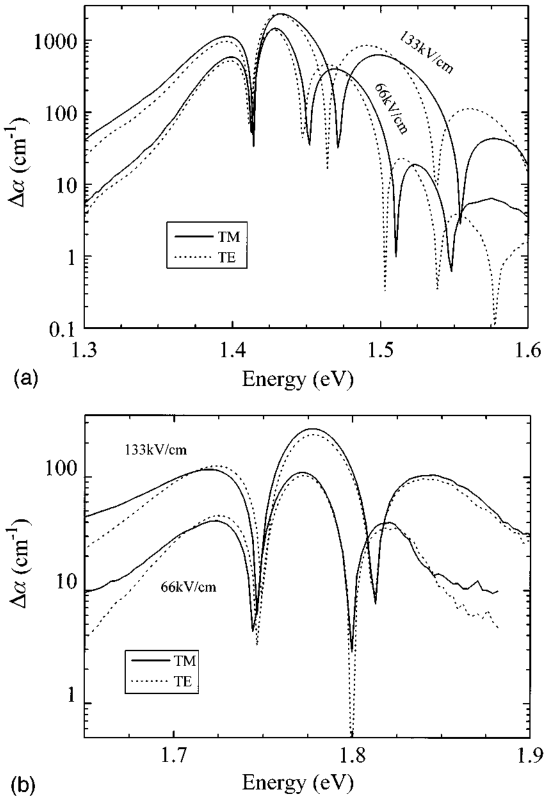

FIG. 3. (a) Logarithmic plot of the electroabsorption of TE- and TM-polarized light near the fundamental band gap of LT-GaAs for applied voltages of 20 and 40 V. (b) Logarithmic plot of the electroabsorption of TE- and TM-polarized light near the split-off band gap of LT-GaAs for applied voltages of 20 and 40 V.

ferent valence bands: the light hole (lh), heavy hole (hh), and split-off (so) valence band. Each term is proportional to the bulk matrix element of the momentum operator and a function containing the overlap integrals of the wave functions. This overlap in turn depends on the effective masses of electrons and holes.

It can be shown that the matrix element of the hh is zero in the case of TM polarized light. Therefore, the TM polarized light only interacts with the lh band, whereas TE polarized light interacts with both, the lh band and the hh band. Taking into account the field and photon energy dependence of the interband matrix elements as well as the different effective masses of lh and hh, a larger absorption for the lh contributions than for the hh contributions is obtained below the band gap. This leads to stronger absorption and absorption changes of TM light in this energy range.

For energies above the band gap the different effective masses of lh and hh are responsible for different oscillation periods of the Franz–Keldysh absorption. For the lh the oscillation periods are larger than for the hh. For this reason the absorption of the TM light is also oscillating with larger periods compared with those of the TE absorption.

At the split-off band-gap energy mainly the split-off valence band contributes to the FKE. The matrix element of this valence band is isotropic and therefore no polarization dependence is expected for the FKE at the split-off band gap.

In summary, we have investigated the FKE on thin LT-GaAs layers for energies between 1.3 and 1.9 eV. The FKE was observable at the fundamental band gap (1.42 eV) as well as at the split-off band gap (1.75 eV). Below the fundamental GaAs band gap TM polarized light shows a stronger Franz–Keldysh absorption than TM polarized light. The period of the Franz–Keldysh oscillations is polarization dependent for the lh/hh-valence band to conduction band transitions and shows no dependence for the transition between the split-off valence band and conduction band.

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