Surface-modified GaAs terahertz plasmon emitter

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We studied the THz emission from n-GaAs plasmon emitters modified by low-temperature-grown (LT) GaAs surface layers. The THz emission is increased since the LT GaAs pins the Fermi level at a midgap position, increasing the surface depletion field. For a THz emitter with a 70-nm-thick LT GaAs layer we observe without external fields a THz emission intensity of 140 nW. In addition, the long-term performance of the modified emitters is improved by the LT GaAs surface layer. © 2002 American Institute of Physics. [DOI: 10.1063/1.1497192]

The process of the generation of electromagnetic waves in the terahertz frequency range (THz emission) from semiconductors by ultrashort light pulses has been known for more than a decade.1 The process itself is based on the instantaneous material polarization2 or on the coherent movement of free carriers.3,4 For the latter case, the intensity and frequency of the emitted terahertz radiation depend on the basic semiconductor material parameters themselves, on the doping level, and on the electric-field strength in the active region of the emitter structure.

THz emission in n-GaAs is achieved due to the coherent plasmon in the n-doped layer. The plasma oscillation of the extrinsic carriers is initiated by the fast change of the electric field in the vicinity of the semiconductor surface induced by electrons and holes, which are injected by an ultrashort optical pulse. Recent experiments and numerical simulations suggest that the electric-field strength in the region of the absorption of the optical pulse is one of the key factors to stimulate a coherent movement of the free carriers.3,5,6 A conventional n-GaAs plasmon emitter utilizes the surface field caused by Fermi-level pinning by the surface states. The density of the surface states, their energy distribution, and charge occupation determine the position of the Fermi level at the surface and the resulting band bending. The magnitude of this bending and its polarity (i.e., depletion or accumulation of the charge carriers) determine the amplitude and the phase of the generated THz radiation.5 When the band bending is reduced due to an externally applied bias,5 or due to oxidation of the surface, the radiated terahertz power from the emitter decreases. The oxidation of the emitter surface can be, for instance, mediated by optically excited carriers for impinging high optical power.7 Thus, the issue of Fermi-level pinning is also important for the long-term stability of the THz emitter performance.

In this letter, we report on the performance of an n-doped GaAs bulk plasmon emitter with an additional low-temperature (LT) GaAs surface layer grown by molecular beam epitaxy (MBE). The thin LT GaAs layer mediates a firm pinning of the Fermi level near the GaAs midgap, hence, a band bending of about 0.7 eV is established. This emitter exhibits an increased power of the THz radiation and better long-term stability when compared to an n-doped GaAs plasmon emitter without LT GaAs surface layer.

In order to take full control over the band bending in the n-GaAs THz emitter structure we can replace the surface states by deep levels of defect states to pin the Fermi level. For such a purpose, a LT GaAs layer grown by MBE is well suited as a surface layer because it contains an abundance of native defects mainly related to an arsenic excess incorporated in the layer.8 The energy level associated with these defects is at a position of about 0.75 eV below the conduction band (Es∼0.75 eV). Due to the high concentration of the defects in the LT GaAs layer (up to 1020 cm−3) the Fermi-level position is firmly pinned close to the GaAs midgap.8 Pinning of the Fermi level by defect states instead of surface states does not change the overall form of the depletion region in the n-doped GaAs layer. For the band-structure calculation of the THz emitter structure (for results, see Fig. 1), we assume a GaAs layer with n doping of 4×1015 cm−3, a LT GaAs layer thickness of 70 nm with deep levels of the concentration of 1020 cm−3 at 0.75 eV below the conduction band, and an inherent surface pinning at the position Es∼0.65 eV. With respect to these chosen data, the band bending for the THz emitter with the LT GaAs surface layer is by about 0.1 eV larger compared to the emitter without LT GaAs layer. This is caused by the difference in the position of the deep levels in the LT GaAs with respect to the pinning position mediated by the surface states. According to

FIG. 1. Schematic drawing and the simple band diagram of n-GaAs (dashed line) and LT/n-GaAs (solid line) bulk plasmon emitter structures.

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a simple model of the plasmon emitter in which the intensity of THz radiation depends on the band bending.\textsuperscript{1} we expect that the output THz radiation from the \textit{n}-GaAs bulk plasmon emitter with a LT GaAs surface layer should be larger than from the emitter without this layer.

Another difference between \textit{n}-GaAs and LT/\textit{n}-GaAs emitters is in the charge sheet density that controls the Fermi-level pinning. If we assume a standard density of the surface states for (001) GaAs surface of $10^{13}$ cm$^{-2}$ eV$^{-1}$ (Ref. 9), and a density of defects related deep levels in LT GaAs of $10^{20}$ cm$^{-3}$,\textsuperscript{7} the corresponding charge sheet densities are $1.5 \times 10^{13}$ and $7 \times 10^{14}$ cm$^{-2}$ for the standard \textit{n}-GaAs emitter and the emitter with a LT GaAs surface layer, respectively. With respect to these data, the emitter with the LT GaAs surface layer should exhibit better performance stability assuming that recharging of the states that pin the Fermi level is relevant.

The plasmon emitter structures used for the experiment are based on a 2-\textmu m-thick Si-doped GaAs epitaxial layer ($n = 4 \times 10^{15}$ cm$^{-3}$) grown by MBE on a (100) semi-insulating GaAs wafer. After the growth of the n-doped GaAs layer the wafer was removed from the MBE chamber and cleaved into quarters. One quarter of the wafer was loaded again into the MBE chamber for regrowth, and after standard surface cleaning, a 70-nm-thick intrinsic LT GaAs layer at 220°C (thermocouple reading) was grown. The LT GaAs layer was subsequently in situ annealed at 600°C for 10 min under As overpressure. This growth procedure yielded two different structures with an identical n-doped GaAs region, hence, with the same key parameters for the coherent plasma oscillation—frequency and excitation damping.\textsuperscript{3}

The terahertz radiation from the emitters was excited by ultrashort (~12 fs) laser pulses centered at a wavelength of 780 nm. We have varied the average optical power used for the excitation of the THz emitters between 0.1 and 190 mW. The generated THz radiation was detected by an autocorrelation technique.\textsuperscript{3} The THz emitter was used either in the Brewster angle geometry, i.e., THz emission was measured in the pseudotransmission, or in the 45° reflection geometry. For both cases, the diffraction-limited THz beam from the emitter was collected and focused by means of two off-axis parabolic mirrors onto the detector. A liquid-helium-cooled Si bolometer was used as an integrating calibrated detector. We have paid large attention to a careful alignment for each tested emitter, hence, the repeated measurements have yielded THz power data within 3% error margin. The autocorrelation setup was enclosed in a sealed box that was purged with dry nitrogen during measurements to suppress absorption of THz radiation by water vapor. The optical beam was mechanically chopped at 220 Hz and the bolometer signal was measured with a lock-in amplifier. Figure 2 shows the autocorrelation signal measured in the Brewster angle geometry for both types of THz emitters and, as a reference, for nominally undoped InAs (\textit{u-InAs}). We have chosen InAs because it is considered as the most efficient THz emitter.\textsuperscript{10} The autocorrelation curves for the GaAs-based emitters have almost the same shape, but the LT/\textit{n}-GaAs emitter exhibits about 25% larger average THz output power than the \textit{n}-GaAs emitter. The spectra corresponding to the autocorrelation signal, obtained by fast Fourier transformation, are shown in Fig. 3. The spectra have a maximum at about 0.7 THz with frequencies extending beyond 2 THz. The full width at half maximum of the spectra is 0.8 THz. The observed peak frequency at 0.7 THz is consistent with the calculated plasma frequency for a doping of $4 \times 10^{15}$ cm$^{-3}$ and does not change with the excitation density.\textsuperscript{3} The InAs emitter exhibited only 24% of the output THz power of the \textit{n}-GaAs emitter. A significant part of the generated THz radiation is absorbed by intrinsic charge carriers (~10$^{15}$ cm$^{-3}$) in the InAs substrate. When measured in the 45° reflection geometry, the output power of the \textit{u-InAs} emitter increases by about a factor of 2.5. The emission spectrum of the \textit{u-InAs} THz emitter has a maximum at higher frequencies than that of the \textit{n}-GaAs emitter due to the lower effective electron mass in InAs.\textsuperscript{3} Moreover, the spectrum of the InAs THz emitter exhibits a shift of the center frequency with the excitation density unlike to the spectra of \textit{n}-GaAs and LT/\textit{n}-GaAs emitters.

The average THz powers from the LT/\textit{n}-GaAs emitter and from \textit{u-InAs} measured by the Si bolometer were 140 and 26 nW, respectively, at an average excitation power of 190...
nW. At the same excitation power and in the 45° reflection geometry we measure 67 and 63 nW from LT/GaAs and u-InAs emitters, respectively. This geometry has larger losses of the pumping optical power due to reflection on the semiconductor surface. However, in the case of the u-InAs emitter, absorption by free carriers in the substrate is in this geometry avoided. We have to note that increasing of the excitation power did not reveal any tendency for saturation of the output THz power from the LT/n-GaAs plasmon emitter, so even larger THz output power is envisaged for higher excitation power. The average THz power of 140 nW measured for the LT/n-GaAs emitter is a large power reported from semiconductors without any external electric or magnetic fields.

The increase of the emitted power from the LT/n-GaAs plasmon emitter was confirmed by an electro-optic sampling technique. This technique allows us to measure directly the electric field of the coherent THz radiation in the time domain and is not sensitive to incoherent thermal radiation that can distort the autocorrelation data from a bolometer. The measured increase in the intensity of the electric field of the THz transients is fully consistent with the increased power obtained from the autocorrelation data.

In addition, we have tested the emitters for their performance stability by performing a set of experiments with the surface oxidation of our THz emitter. The n-GaAs emitters with and without LT GaAs layer have been oxidized in water vapor at 450 °C for 30 min. Figure 4 presents the relative magnitude of the total THz radiation for the n-GaAs and LT/n-GaAs emitters before and after oxidation. While the emitter structure with the LT GaAs layer exhibits no significant change in the output THz power when exposed to oxidation, the THz power from the n-GaAs emitter is decreased by 30%. After removing of the oxide layer by etching in ammonia water solution, the magnitude of the THz radiation from the n-GaAs emitter was recovered (Fig. 4).

The observed sensitivity of the THz radiation intensity to the GaAs surface oxidation can be well explained by a change of the surface pinning of the Fermi level. The surface of GaAs is typically covered by a 2–5-nm-thick native oxide consisting of a mixture of gallium and arsenic oxides. This oxide layer together with the surface nonstoichiometry are responsible for the Fermi-level pinning at the surface and for the resulting band bending. Therefore, if the energy distribution and density of the surface states are changed via an intentional oxidation of the GaAs surface, the change in the oxide layer thickness and composition leads to changes in the Fermi-level pinning at the surface. Our results suggest that for the n-doped GaAs emitter after oxidation the Fermi level at the surface was shifted towards the conduction band, and thus the band bending, and consequently the emitted THz radiation, were reduced. The etching of the GaAs surface has removed the layer formed by the intentional oxidation and reestablished the initial surface pinning of the Fermi level. In the case of the LT GaAs surface layers, the band bending in the n-doped GaAs layer is no longer determined by surface states. In addition, high resistance of the LT GaAs against oxidation was reported. Therefore, no significant influence of the oxidation was found for the THz emitter with the LT GaAs layer.

In conclusion, we have improved the performance of the n-GaAs plasmon emitter by adding a LT GaAs surface layer. The emitter with this layer exhibits an increased power of the emitted THz radiation, which is explained in terms of Fermi-level pinning at the surface by midgap states in the LT GaAs. The measured average THz power of 140 nW from the emitter is large power reported for plasmon emitters without any external electric or magnetic fields. In addition, the LT GaAs surface layer efficiently increases the emitter stability when the emitter is exposed to an oxidizing environment.

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9 Properties of Gallium Arsenide, EMIS Datareviews Series No. 2 (INSPEC, London, 1990), Ch. 15.