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1550 nm ErAs:In(AI)GaAs large area photoconductive emitters

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We report on high power terahertz (THz) emission from ErAs-enhanced In_{0.52}Al_{0.48}As-In_{0.53}Ga_{0.47}As superlattices for operation at 1550 nm. ErAs clusters act as efficient recombination centers. The optical power is distributed among a large, microstructured area in order to reduce the local optical intensity. A THz field strength of 0.7 V/cm (1 V/cm peak-to-peak) at 100 mW average optical power has been obtained, with emission up to about 4 THz in air, limited by the detection crystal used in the system. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4750244>]

Photoconductive terahertz (THz) emitters and detectors are used in a multitude of setups,^{1–4} particularly in pulsed THz time domain systems. These systems are typically operated at a wavelength of 800 nm with low temperature (LT) grown GaAs photoconductors. The telecom frequency range around 1550 nm is, however, much more attractive in terms of system cost, size, and availability of components. Unfortunately, the materials properties of photoconductors at 1550 nm are much worse than those of LT-GaAs at 800 nm. The requirement of a much lower band gap for operation at 1550 nm strongly increases the dark currents. Electrical heating by the required DC bias and optical heating due to absorption further worsens the situation, leading to thermal runaway and finally destruction of the device. A way around this issue may be unbiased photo-Dember emitters,⁵ where no external biasing is required: Concentration gradients of photo-excited carriers and different mobilities of electrons and holes lead to THz emission. However, the THz signal cannot be electrically modulated for lock-in detection as in the case of photoconductors, impeding chopping at high speeds. For antenna-coupled photoconductors at 1550 nm, short lifetimes are required to both reduce the conductivity and the lifetime roll-off.^{3,6} Low temperature grown InGaAs is highly n-type since the trap states are close to or even in the conduction band, in contrast to their LT-GaAs counterpart with close to mid-gap states.⁷ A reduction of the lifetime could be demonstrated by using low temperature grown InAlAs, showing efficient recombination, followed by InGaAs absorption regions in a superlattice.^{3,8} Another option is heavy ion bombardment with high kinetic energy, generating efficient trap states. A lifetime of 0.46 ps has been reported.⁹

Here, we report on incorporation of ErAs nanoparticulates as recombination centers. We implemented the short lifetime material in a large area emitter (LAE) geometry, which has been proven to be very efficient for high power, ultra-broadband THz generation.^{10–14} In contrast to continuous-wave operated antenna-coupled emitters, pulsed LAEs do not require a short lifetime.^{12,14,15} The ErAs recombination centers, however, assist to drastically increase the resistance of the sample by a factor of at least 45 compared to unintentionally doped intrinsic InGaAs. This allows for much higher biasing levels, resulting in a drastic increase of

THz power. We demonstrate operation up to about 4 THz, even without nitrogen purging. This bandwidth is about a factor of two larger than obtained with photo-Dember emitters at 1550 nm.⁵ A THz peak field strength of 0.7 V/cm has been measured when the emitter is operated at room temperature.

The cross section through the sample is illustrated in Fig. 1. A large area with a circular shape of 800 μm diameter, resulting in an active area of 0.5 mm² is microstructured with interdigitated electrodes with a gap of either 6 or 12 μm . Every second gap is either blocked or etched away in order to allow for uni-directional motion of carriers only. In order to prevent oxidation of the sample, it was coated with a 200 nm thick Si₃N₄ anti-reflection coating. Instead of using an antenna,¹⁶ the carriers generated within the large area emit the THz radiation directly.^{14,15} Photo-generated electrons and holes are accelerated by the external bias applied between the electrodes. The accelerated motion of the carriers generates THz radiation until they start scattering or are captured by trap states. During scattering, they are decelerated, resulting in radiation, too, till they reach the saturation velocity. Since the carriers are accelerated in-plane, the LAE emits perpendicular to the surface, mainly into the substrate, since its radiation impedance is lowered by the refractive index of the InP substrate, n_{InP} . The effective radiating aperture is the whole area, which is much larger than the center wavelength. Due to the coherent emission of the whole area, the emitter provides a diffraction-limited Gaussian beam, not requiring a silicon lens for out-coupling. A detailed discussion of the emission concept can be found in Refs. 14 and 15.

The photoconductor consists of a superlattice of 70 periods of 15 nm In_{0.53}Ga_{0.47}As, 2.5 nm In_{0.52}Al_{0.48}As, 0.8 monolayers of ErAs, and 2.5 nm In_{0.52}Al_{0.48}As. The InGaAs layers serve as absorption regions. The 0.8 monolayers of ErAs buried within the 5 nm InAlAs layer provides ErAs particulates as trap states. Unlike in InGaAs, the ErAs forms deep traps in InAlAs with short lifetimes. The ErAs layer is beryllium co-doped with a nominal p-type concentration of $p(\text{Be}) = 5 \times 10^{13}/\text{cm}^2$ to compensate for the n-type background of ErAs. The Hall mobility was measured to $1380 \pm 200 \text{ cm}^2/(\text{Vs})$, much higher than obtained for LT-GaAs, and comparable to the values presented in Refs. 3 and 17. The lifetime was determined by

FIG. 1. Schematic layout of the large area emitters. Mesa height ($1.4\ \mu\text{m}$) and width ($15\text{--}24\ \mu\text{m}$ for the $12\ \mu\text{m}$ gap designs) are not to scale. (a) Conventional design: Every second gap is blocked by a metal shadow mask on a dielectric SiN spacer. Contacts are attached to the top. (b) Lateral contact design: The photoconductive material in every second gap is removed. The contacts are attached to the top and the sides of the mesa, improving the lateral transport.

optical pump-probe measurements at $1550\ \text{nm}$ to $2.2 \pm 0.6\ \text{ps}$. Much shorter lifetimes of down to $0.3\ \text{ps}$ have been reported on other ErAs:InGaAs samples where higher concentrations of ErAs were incorporated.^{18,19} However, the high content of ErAs particulates increases the carrier scattering rate and hence reduces the mobility. It also increases the n-type background, requiring higher p-type compensation doping levels. Both effects impede the THz performance of the LAE under pulsed excitation: For the LAE emitter, the acceleration of the carriers within the photoconductive material and the effective dipole length, created by separated electrons and holes during their acceleration by the external bias, are relevant for the THz emission.¹⁴ This requires low scattering rates. Since the generation and transport takes place in the undoped InGaAs layers, much higher mobilities (and, hence, lower scattering rates) than in typical low lifetime materials, such as LT-GaAs, were obtained. For efficient operation, a large DC resistance is required. At the maximum bias, the device performance of $1550\ \text{nm}$ LAE emitters is typically limited by thermal heating, $P_{th} = U_{DC}^2/R_D \sim R_D^{-1}$, not by electrical breakdown. We therefore used a material with longer lifetime where a high DC resistance is easier to engineer. The growth of ErAs:InGaAs is described elsewhere.^{19,20}

The THz setup consists of a Toptica FFS $1550\ \text{nm}$ mode-locked fiber laser with a pulse duration of $100\ \text{fs}$, a repetition rate of $78\ \text{MHz}$, and an optical power of $100\ \text{mW}$. The $1550\ \text{nm}$ signal is split into two parts. The first signal is focused on the LAE to generate the THz radiation. The second signal is frequency doubled, combined with the THz signal and both are focused on a ZnTe crystal with a thickness of $200\ \mu\text{m}$ for electro-optic detection. The power of the $775\ \text{nm}$ probe pulse was $0.5\ \text{mW}$. A balanced photodetector setup is used to read out the polarization change of the probe pulse which is proportional to the incident THz signal. The

setup was not evacuated nor purged with dry nitrogen. The beam is collimated and refocused by a pair of off-axis parabolic mirrors of equal focal length. The optical path length of the THz beam was approximately $29\ \text{cm}$. It was operated at 26°C at a relative humidity of 37% , resulting in significant attenuation of the signal above $1\ \text{THz}$. From the water absorption, we estimate an attenuation of about 30% of the THz power. The $12\ \mu\text{m}$ spaced contacts are biased with a rectangular AC voltage with peak-to-peak biases up to $21\ \text{V}_{pp}$, symmetric around $0\ \text{V}$ at $30.4\ \text{kHz}$ modulation rate. A lock-in amplifier is used to read out the differential signal of the balanced photodetectors. For heat spreading, the sample was mounted on a $0.5\ \text{mm}$ thick semi-insulating ($R > 10\ \text{k}\Omega\text{cm}$) piece of silicon, followed by an aluminum body using heat sink compound.

Fig. 2 shows a typical pulse shape and frequency spectrum of the generated THz pulse of a sample with $12\ \mu\text{m}$ gap with lateral contacts as shown in Fig. 1(b) and an attached heat spreader as described above. A DC bias modulation of $20\ \text{V}_{pp}$ ($21\ \text{V}_{pp}$) was applied resulting in a total current of $50\ \text{mA}$ ($65\ \text{mA}$) in thermal equilibrium at $100\ \text{mW}$ ($35\ \text{mW}$) optical power. The oscillations after the main pulse originate mainly from the heat spreader. This was verified by removing it. The Fourier spectra show emission of the sample up to $4\ \text{THz}$. The emission at the high frequency end is mainly limited by water absorption within the setup and the ZnTe crystal. It becomes lossy above $3\ \text{THz}$ ²¹ and the rectification coherence length drops below the crystal thickness of $200\ \mu\text{m}$ due to the increasing refractive index when approaching the TO phonon mode.²² The peak pulse field strength was determined to $0.7\ \text{V/cm}$ with a peak-to-peak field strength of $1\ \text{V/cm}$. This is by almost a factor of two higher THz field than generated with InGaAsN samples at the shorter wavelength of $1.3\ \mu\text{m}$.¹¹ The dynamic range is

FIG. 2. (a) Pulse shape of the generated THz signal at $1550\ \text{nm}$ operation frequency in the time domain at $20\ \text{V}_{pp}$ bias (black) and at $780\ \text{nm}$ operation wavelength and $18\ \text{V}_{pp}$ bias and $100\ \text{mW}$ optical power. The peak to peak field strength is $1\ \text{V/cm}$ at $1550\ \text{nm}$. (b) Fourier transform of the $1550\ \text{nm}$ signal shown in (a).

47.8 dB at a few 100 GHz and still 40 dB at 2 THz at a lock-in time constant of 1 s (24 dB/octave filter attenuation). We compared the performance of the sample with lateral contacts (Fig. 1(b)) to a conventional design (Fig. 1(a)) at a lower bias of 6 V_{pp}. The lateral contact design provided 60% higher THz field amplitude. The lateral contacts aid in increasing the maximum output power due to a more homogeneous field distribution. This increases the contribution to the emitted THz field of carriers generated within the material since the accelerating fields are similar throughout the penetration depth of the optical beam. Furthermore, every second gap has been removed, reducing the current generated by the device and therefore the heat, allowing for a higher DC bias. Samples with 6 μm gap size emitted slightly less power. Since the gap size is a factor of two smaller but the total area was identical, more heat was generated which limited the maximum bias. Furthermore, the electrode layout covered more area, reducing the photocurrent.

In order to further investigate the performance of the lateral contacts, we also tested an emitter at an operation wavelength of 780 nm. The specifications of the setup were very similar to the 1550 nm setup, namely a pulse duration of about 80 fs, a repetition rate of 78 MHz, and a ZnTe detector crystal of 500 μm length. Since the absorption coefficient of InGaAs is much higher at 780 nm, the current densities close to the surface are much larger and the penetration depth is much shorter. The two designs shown in Fig. 1 should therefore behave very similarly, since the carriers generated close to the surface experience the same accelerating field strength at the same biasing conditions. This is in perfect agreement with the experiment, where the fields generated by both designs deviated by only 2%. In contrast, the lateral design (Fig. 1(b)) provided an increase of the THz field by 60% at 1550 nm. This increase is attributed to the more homogeneous fields throughout the structure, resulting in more efficient carrier acceleration in the depth.

The maximum field strength for operation at 780 nm and 97 mW optical power were obtained with 18 V_{pp}. This slightly smaller bias, compared to the 1550 nm measurement, was chosen in order to limit the local heat generation by the higher currents close to the surface. A peak THz field strength of 0.4 V/cm was measured. The smaller field strength is attributed to the smaller DC bias, the fact that the lateral contact layout is less helpful if the carriers are generated close to the surface, and the excitation of carriers high into the bands, resulting in strong inter-valley scattering. At a ten times shorter lock-in time constant than that used in the 1550 nm measurements (100 ms, 24 dB/octave filter attenuation), we obtained a dynamic range of 51 dB below 1 THz and still 35 dB at 2 THz due to a less noisy laser system.

In the following, we want to summarize the limiting factors for higher power generation and to give a brief outlook on possible improvements.

The peak powers are yet thermally limited due to ohmic heat. Right after the bias is switched on, the current at 20 V_{pp} bias is about half of that when a steady state is reached. Since InGaAs is effectively a negative temperature coefficient (NTC) resistor, heat populates the conduction band thermally, reducing the resistance of the device. At a constant external bias, the current therefore increases. This

results in a further increase of the thermal power deposited in the device, since $P_{th} = U^2/R_D$, further reducing the resistance. The device current walks off till the temperature gradient between device and heat sink is sufficient to maintain a steady state. We could maintain a steady state up to bias of 21 V_{pp} for 35 mW optical power and 20 V_{pp} for 100 mW of optical power. No degradation of the IV characteristics was found after applying 21 V_{pp} bias. From measurements on interdigitated structures with 2 μm gap, we conclude that the breakdown field strength of the material is about 10 times higher than the fields used here, showing that the device operation is purely thermally limited.

At a peak bias of 10 V, corresponding to 20 V_{pp}, a total current of 50 mA (45 mA) was measured at an optical power of 100 mW (35 mW) resulting in ohmic heat of 500 mW, already including the contributions from the photocurrent. The additional heat due to optical absorption is therefore much smaller than the electrical heat generated within the device. There was almost no influence on the maximum tolerable bias when the optical power is reduced from 100 mW to 35 mW as shown in Fig. 3. At 10 V peak bias (20 V_{pp}), a reduction of the total current of only about 5 mA, corresponding to 10% was found, despite the reduction of the optical power by a factor of 2.85. The maximum bias before thermal runaway occurred was only 0.5 V higher at 35 mW optical power. We conclude that the optical power may therefore be increased to a few 100 mW before its influence on the thermal management becomes significant. This strongly increases the share of the photocurrent and, consequently, the THz power. Unfortunately, the optical system did not allow for higher optical powers.

Improvement of heat removal will drastically improve the peak THz emission. To show the drastic effect, we removed the Si heat spreader from the backside of the chip. At a peak bias of 4 V, the current was greater than 21 mA. With the Si heat spreader, the current was only 12.9 mA for a device as illustrated in Fig. 1(a). More efficient heat removal as shown in Ref. 23 by using diamond heat spreaders will further improve the emitted power. This would, in turn,

FIG. 3. Thermal runaway of the sample at a constant optical power of 35 mW and 100 mW. The total steady state current increases highly nonlinear with bias when heat removal becomes insufficient above a peak bias of about 8 V (16 V_{pp}).

allow for higher biases. Since the heat generation for these InGaAs devices is almost independent of the optical signal, blocked and optically activated gaps for the conventional design in Fig. 1(a) contribute similar amounts of heat, whereas etched gaps in Fig. 1(b) are highly resistive due to the semi-insulating InP substrate. We could therefore use much higher biases for the lateral contact design.

A relatively simple way to reduce the thermal load of the device is bias triggering. Bias at the sample is only required when the optical pulse is incident. Therefore, a photodiode could be used to trigger a short bias window of width Δt . The thermal load would therefore be reduced by the product of the bias window size and the repetition rate, $\eta = \Delta t \nu_{rep}$.

In conclusion, we have demonstrated ErAs:In(Al)GaAs photoconductive emitters in a large area emitter layout for efficient photoconductive devices operated at the attractive telecom wavelength range. A THz field strength of 0.7 V/cm (1 V/cm peak-to-peak) was demonstrated at excitation with 1550 nm pulses and 0.4 V/cm with 780 nm excitation of 100 mW using a design with lateral contacts. Much higher optical excitation powers can be used in order to further increase the THz power, since the maximum power was thermally limited by the ohmic heating within the device. The breakdown field of the material was determined to be about a factor of 10 higher than used here. This should allow much more efficient THz generation with optimized thermal management. We have pointed out several options to remove heat and to reduce the thermal load. The emitters are scalable, allowing for much higher THz power levels if sufficient optical power and heat removal are available.

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