Terahertz Sources Based on Emission from a GaAs/(Al,Ga)As Heterostructure at Cryogenic Temperatures

D. Yavorskiy,[1,2] M. Szoła,[2] T. Tarkowski,[1] J. Wróbel,[3] P. Nowicki,[3]
V. Umansky,[4] W. Knap,[1,5] and J. Łusakowski[1,*]

[1] *Faculty of Physics, University of Warsaw, ul. Pasteura 5, Warsaw 02-093, Poland*
[2] *CENTERA Laboratories, Institute of High Pressure Physics, Polish Academy of Sciences, ul. Sokołowska 29/37, Warsaw 01-142, Poland*
[3] *Institute of Physics, Polish Academy of Sciences, al. Lotników 32/46, Warsaw 02-668, Poland*
[4] *Weizmann Institute of Science, Rehevot 76100, Israel*
[5] *Laboratoire Charles Coulomb (L2C), UMR 5221 CNRS—Université de Montpellier, F-34095 Montpellier, France*

(Received 28 July 2021; accepted 9 September 2021; published 1 October 2021)

A high-electron-mobility GaAs/$Al_{0.36}Ga_{0.64}As$ heterostructure is processed by electron-beam lithography to fabricate samples with a separation of the current-supplying Ohmic contacts of between 28 μm and 1.3 mm. Voltage pulses of 20-ms duration, with a 4% filling factor and an amplitude up to 30 V, stimulate terahertz emission from samples cooled to 4 K. The radiation spectrum, centered at about 390 GHz (about 1.6 meV), registered with a Fabry-Perot interferometer, shows almost no dependence on the applied voltage or on the shape of the sample. The emission appears in a threshold manner and is accompanied by a jump of current by more than 2 orders of magnitude. The energy of the emitted photons is about three times smaller than in the case of any previously reported impurity-related emission from either bulk GaAs or GaAs-based quantum wells. The emission is interpreted as resulting from a two-step ionization-recombination process involving shallow donors in the (Al,Ga)As barrier, which create bound states of electrons in the GaAs quantum well. Thus, the frequency of emission is argued to be tuned by the width of the spacer layer. We present these as small convenient sources that can be used for calibration and check-up operation of cooled bolometric systems used in astronomical observations.

DOI: 10.1103/PhysRevApplied.16.044001

I. INTRODUCTION

The generation of terahertz radiation by electrical excitation of a semiconductor device is one of the most challenging goals of the technology of submillimeter waves. Experiments show that the conversion of electrical to optical power in such devices is rather low, which stimulates a permanent quest for new solutions. In spite of the technological difficulties, there are a few types of quite powerful semiconductor devices, such as electronic frequency multipliers [1], resonant tunneling diodes [2], field-effect transistors [3], and quantum cascade lasers [4], which are able to generate up to tens of milliwatts of optical power at terahertz frequencies.

On the other hand, there are some solutions that are still closer to the basic research than commercial devices, such as emitters based on transitions between Landau levels [5] or between shallow impurity levels [6]. The present paper describes this kind of device, in which the emission of terahertz radiation from a high-electron-mobility GaAs/(Al,Ga)As heterostructure is proposed to follow the ionization of shallow donors and a radiative relaxation of the electrons within a triangular quantum well. The terahertz source described is operational at cryogenic temperatures and its advantage stems from its small size, low power consumption, and low fabrication cost. We also argue that the frequency of the emitted radiation is determined by the distance from the doping layer in the (Al,Ga)As barrier to the GaAs/(Al,Ga)As interface (i.e., by the width of the spacer), which provides the possibility to tune the emitted frequency.

The generation of terahertz radiation following the ionization of shallow donors has been observed both in epitaxial layers [6–9] and in quantum wells [10–12]. A characteristic feature of the registered spectra is a correspondence of the energy of the emitted photons with the energy separation of the shallow impurity levels. For this reason, in the case of bulk GaAs doped with shallow donors, a low-energy cutoff of the spectra thus obtained

*jerzy.lusakowski@fuw.edu.pl

is situated at about 4.4 meV, which corresponds to a 2*p*-1*s* transition of a shallow donor in this material. In the case of GaAs-based quantum wells, the emitted energy is much higher (about 20 meV), which reflects the fact that in a quantum well, an electron is bound to a shallow donor much more strongly than in a bulk material [13].

In the present study, we report on terahertz emission from a GaAs-based heterostructure with the spectrum centered at about 390 GHz, which corresponds to 1.6 meV. Such a low energy of emitted photons cannot be attributed to transitions between levels of a shallow donor in the system under consideration and does not suit any previously described mechanisms of terahertz emission from GaAs or GaAs-based structures. The interpretation proposed refers to localized states of electrons in the GaAs quantum well, which are bound by ionized shallow donors in the (Al,Ga)As barrier of the heterostructure.

II. SAMPLES AND EXPERIMENTAL SETUP

The samples used in the experiments are processed by electron-beam lithography on a high-electron-mobility GaAs/$Al_{0.36}Ga_{0.64}As$ heterostructure, with a two-dimensional electron gas (2DEG) residing at 108 nm below the surface of the sample. The wafer used is grown using molecular-beam epitaxy, the electron mobility and electron concentration n_s being equal to 2.7×10^6 cm^2/Vs and 2.8×10^{11} cm^{-2} at 4 K, respectively. Two samples (called S_1 and S_2) of different dimensions are prepared with Au/Ge/Ni current-supplying contacts. Each of the samples is a rectangular mesa, with the separation of the contacts equal to 1.3 mm for sample S_1 and 28 μm for S_2, while the widths of the channels are 48 μm and 0.37 mm, respectively (see the inset to Fig. 1).

A scheme of the experimental setup is presented in Fig. 1. The samples are placed in a variable-temperature insert in a liquid-helium cryostat supplied with a superconducting coil and cooled down to 4 K. The samples are mounted at the end of a waveguide (a stainless steel tube of 18 mm in diameter and with a length of 130 cm), which is sealed at the opposite end with a 1-mm-thick crystalline quartz window. A Golay cell is mounted on a motorized translation stage just above the window. This configuration of devices acts as a Fabry-Perot interferometer, with the cavity of the interferometer formed by the window of the Golay cell and the quartz window of the insert. The experimental setup is tested at room temperature by placing the output of a tunable electronic source at the position of the sample. The spectra obtained for two monochromatic lines of frequency equal to 215 GHz and 630 GHz are shown in Fig. 2(b).

The length of a step and the range of the Golay-cell movement are equal to 50 μm and 15 mm, respectively. Rectangular voltage pulses of duration 20 ms and period 0.2 s are applied to the Ohmic contacts; the amplitude of

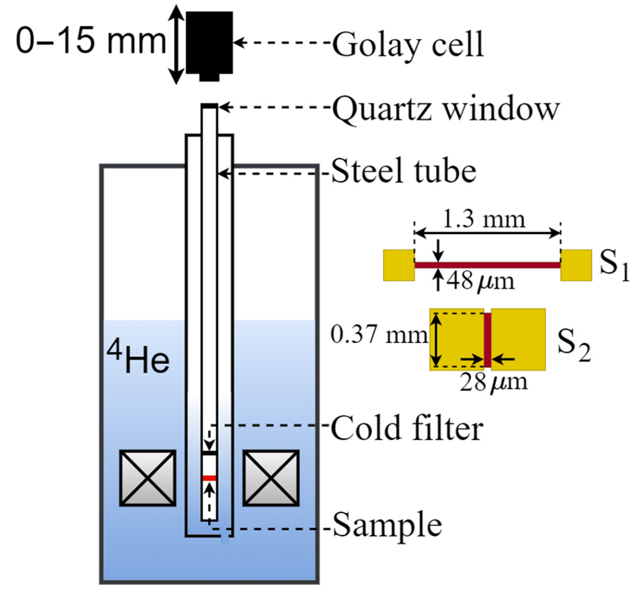

FIG. 1. A schematic of the experimental setup. The inset (not to scale) shows a top view of the samples studied, with dimensions of the current-conducting channels as indicated.

the pulses is varied between 0 and 30 V. The signal from the Golay cell is registered using a lock-in technique and the current flowing through the sample is measured as a voltage drop on a 10-Ω resistor connected in series with the sample.

The parameters of the voltage trails are chosen so as to avoid heating of the samples, which could result in their subsequent degradation. With the filling factor of the voltage trails equal to 4%, we can observe a stable generation of radiation over long periods without any changes of the signal; typically, the stability of the emission is tested under different biasing conditions for periods longer than 10 h. Due to the low intensity of the signal, the spectra are averaged. We would like to stress that the emission is only observed with a cold filter installed close to the sample, its role being to block 300-K background radiation. As is shown below, we observe only a slight evolution of the shape of the spectrum with the amplitude of the pulses. From the calibration of the Golay cell and the known damping of the waveguide and quartz window, we estimate the total emitted power at the level of 10 μW.

III. RESULTS

Figure 2 shows spectra of the radiation emitted from samples S_1 and S_2 as a function of the voltage applied to the Ohmic contacts. One can note that the spectra for both samples are essentially identical, with a slight broadening toward the high-frequency tail upon an increase of the amplitude of the voltage pulses.

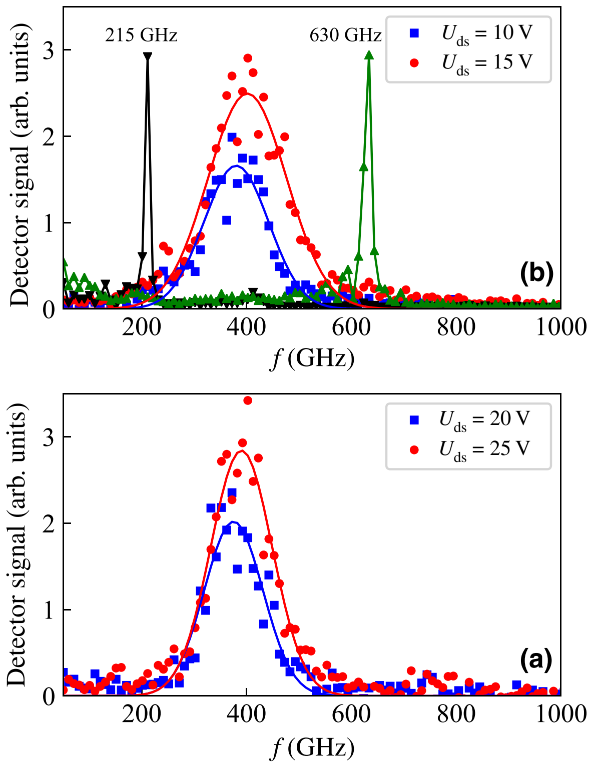

FIG. 2. (a) The spectra of the radiation emitted from sample S_1 at different amplitudes of the voltage pulses: 20 V (bottom) and 25 V (top). (b) The spectra of the radiation emitted from sample S_2 at different amplitudes of the voltage pulses: 10 V (bottom) and 15 V (top). The spikes marked 215 GHz and 630 GHz are the spectra of monochromatic radiation.

In Fig. 3, we compare the evolution of the power of the emitted terahertz signal and the current-voltage (I-V) characteristic of sample S_2. One can note a strong correlation between these two signals: the emission appears in synchronization with a large jump of the current. The emission spectra and the I-V characteristics are measured at different magnetic fields ranging up to 0.1 T. The inset to Fig. 3 shows that the threshold voltage is strongly dependent on the magnetic field. In Fig. 4, we present the spectra of the emission of sample S_2, biased with 12 V at different magnetic fields. As can be seen, a magnetic field as low as about 0.1 T switches off the emission. The features of the emission presented in Figs. 3 and 4 are the same for both samples S_1 and S_2.

To summarize the experimental results, we observe terahertz emission from a GaAs/(Al,Ga)As heterostructure that: (a) shows a spectrum that is identical for both studied samples, of essentially different sizes; (b) occurs in a threshold manner once the amplitude of the bias voltage is high enough and its appearance coincides precisely with a jump of the current by more than 2 orders of magnitude; (c) shows only a small dependence of the spectrum on the amplitude of voltage pulses; (d) and vanishes in

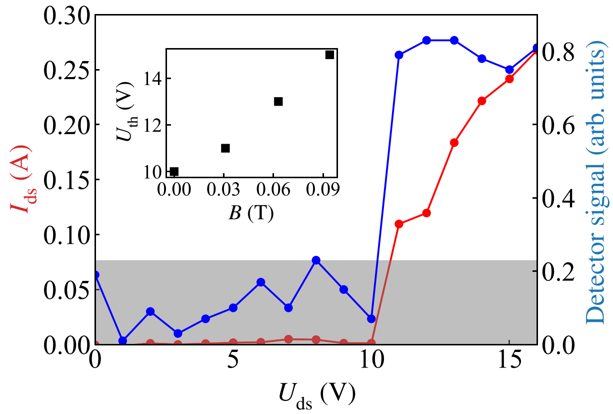

FIG. 3. The I-V characteristics of sample S_2 (left scale) and the intensity of the terahertz emission (right scale). The gray rectangle describes the noise level of the detector. The inset shows the dependence of the threshold voltage on the magnetic field for sample S_2.

a weak magnetic field, at a temperature higher than 10 K and also at 4 K if a cold filter is not used to cut off background room-temperature radiation. We understand the temperature dependence in point (d) to be a signature of photoionization of weakly bound states by the background radiation.

IV. DISCUSSION

The two samples studied differ in their channel dimensions (the channel of S_1 is 46 times longer than that of S_2), yet the emission spectra from the two samples are almost identical. This may indicate that the mechanism behind the emission is related to intrinsic properties of the $GaAs/Al_{0.36}Ga_{0.64}As$ heterostructure. This fact excludes a relationship of the observed emission with the Gunn effect,

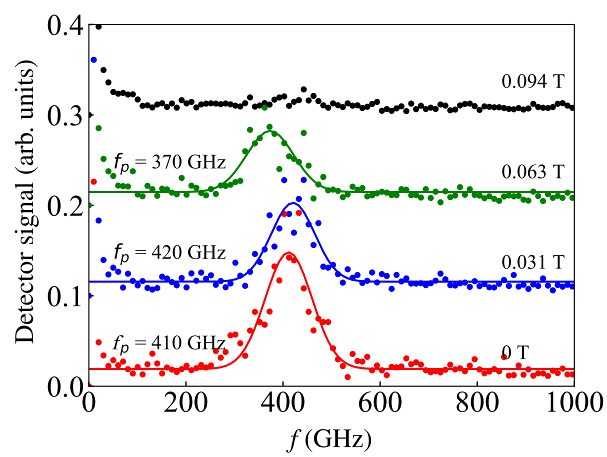

FIG. 4. The spectra of the radiation emitted from sample S_2, biased with voltage pulses, with the amplitude equal to 12 V measured at different magnetic fields.

as this effect is related to the time of flight of a Gunn domain between Ohmic contacts.

Another mechanism responsible for the emission of terahertz radiation from quantum wells may be related to plasma excitations that can be tuned by the geometry of the sample. For example, in Ref. [14], an emission of terahertz radiation from electrically excited plasmons in a $GaAs/Al_{0.3}Ga_{0.7}As$ heterostructure has been observed. The emission is observed from two samples with different periods (2 μm and 3 μm) of diffraction gratings covering the channel of the sample. The energy of the emitted terahertz radiation is defined by the grating periods: for a grid with a period of 3 μm, the energy of the photons is equal to 2 meV, while for a grating with a period of 2 μm, the energy is equal to 3 meV. The samples that we study, however, are not covered with metallic grids or other periodic structures; therefore, the emission mechanism described in Ref. [14] cannot be applied to the emission discussed in the present work.

However, it is not necessary to cover the conducting channel with a diffraction grating to excite plasmons in a 2DEG. In Ref. [15], for example, it has been shown that in structures not covered by metallization, plasmons can be excited on some geometric details of extension Λ in the channel containing a 2DEG and then the wave vector of the nth plasmonic mode is given by $k_n = 2n\pi/\Lambda$, where n is an integer. Such a geometric detail may be, for example, the length or width of the channel. The dependence of the plasmon frequency f_n on its wave vector is given by the following equation:

$$f_p = \frac{1}{2\pi}\sqrt{\frac{n_s e^2 k_n}{2m^* \epsilon_0 \epsilon(k_n)}}, \tag{1}$$

where m^* is the electron effective mass and ϵ_0 and $\epsilon(k_n)$ are the dielectric permittivity of the vacuum and the effective dielectric constant, respectively. If we consider the possibility of generating a plasmon with a frequency of 400 GHz, then, according to Eq. (1), Λ should be equal to approximately 5 μm. Since the samples studied do not involve details of a comparable extension, we conclude that a plasmonic emission mechanism is not applicable in this case.

Features (b), (c), and (d) of the emission suggest a mechanism associated with the ionization of shallow donors. In particular, they are in agreement with an influence of the magnetic field on the ionization of shallow donors as described in Refs. [16,17]. A relationship between terahertz radiation emission and the ionization of shallow impurities is known both in the case of GaAs bulk crystals (epitaxial layers) [6,7] and GaAs/(Al,Ga)As quantum wells [11,18–20]. In both cases, the emission is referred to recombination transitions between energy states of impurities, which are first ionized as a result of the application of a bias. On the other hand, in the case of works related to quantum wells, the observed recombination transitions may in principle also occur between the electrical states of the quantum well and between the electrical states of the well and the energy levels of the impurities, if such transitions are not forbidden by selection rules or momentum conservation. It should be emphasized that in the case of emission from epitaxial layers, the ionization of shallow impurities is always clearly attributed to impact ionization, while in works related to quantum wells, the notion of impact ionization does not appear at all. Instead, the authors use the term *impurity breakdown* [11,18,19]. Similar to the case of epitaxial layers, the emission from quantum wells also appears in a threshold manner if a threshold bias voltage is exceeded (however, in Ref. [20] no information is given about the emission threshold).

Typical results of terahertz emission from bulk GaAs are described in Ref. [6], where the epitaxial layer used contains shallow donors and acceptors with concentrations equal to 2.5×10^{14} cm^{-3} and 1.6×10^{14} cm^{-3}, respectively. The observed emission spectrum ranges from 3 meV to 9 meV and consists of a narrow peak with an energy of 4.4 meV, which corresponds to $2p$-$1s$ radiative transition, and a tail extending to 9 meV, associated with recombination transitions of hot electrons to energy states of shallow dopants. In that work, the emission spectrum does not depend on the applied electric field up to a value of 50 V/cm. The change in the current flowing through the sample after exceeding the threshold voltage for impact ionization is of 6 orders of magnitude. In Ref. [7], the emission of terahertz radiation from a GaAs epitaxial layer is also observed but with a concentration of impurities in the layer about 40 times greater than in Ref. [6]. The emission spectrum in Ref. [7] differs from that in Ref. [6]: it ranges from 2.5 meV to 15 meV and shows a richer spectral structure—the additional peaks in the emission spectrum are attributed to transitions between other impurity states, without naming these states explicitly.

In the case of GaAs-based quantum wells, the situation is as follows: in all works found in literature databases, terahertz emission is observed from superlattices (e.g., 200 periods in Ref. [18]) intentionally doped at the center of each well. In the case of Ref. [18], the impurity is beryllium (a shallow acceptor), while in the case of Ref. [11,19], it is silicon (a shallow donor). The emission spectrum ranges, respectively, from 10 meV to 60 meV in Ref. [18] and from 6 meV to 19 meV in Ref. [19]. According to interpretations included in the cited papers, the maxima observed in the spectra may be related to the relaxation of hot electrons to the ground state of shallow donors [11], transitions between energy levels of shallow impurities [11,18–20], or transitions between the electrical states of a quantum well and impurity states [19,20].

In Ref. [11,19], the tested samples are cooled to 4.2 K; in Ref. [20], the temperature of the samples is between

5 and 10 K; and in Ref. [18], the temperature is −15 K. In Ref. [11,18,19], the authors point out that the emission starts after surpassing a threshold electric field that causes a breakdown, but they do not specify the breakdown mechanism.

In the aforementioned works on quantum wells, doping is intentionally introduced to increase the concentration of carriers in the quantum wells. For this reason, the threshold nature of the emission can be related to the ionization of shallow impurities present in the quantum wells. The heterostructure studied in this work is a material of a high purity—there are only residual impurities in the GaAs channel. The observed current jump at the emission threshold is more than 2 orders of magnitude smaller than in the case of typical *n*-type GaAs epitaxial layers [6] or doped quantum wells [11]. On the one hand, the smaller current jump could be explained by a low concentration of residual impurities but on the other, as it is clear from the above literature research, the observed emission cannot be attributed to any of the above-mentioned mechanisms, since the energy of the emitted photons is at least three times smaller than that previously reported [18–20].

Thus, the new result described in the present work is a small energy value of photons emitted from a heterostructure doped in the barrier (1.6 meV ↔ 400 GHz). Let us recall that the energy separation between 1*s* and 2*p* states in a shallow donor in GaAs is $3Ry/4 \approx 4.4$ meV (where the effective Rydberg in GaAs is equal to $Ry = 5.88$ meV [21]) and that this value is larger in quantum wells, where it becomes dependent on the spatial position of a donor with respect to the well barriers [13]. We note that there are strong indications that the observed emission is related to the ionization of shallow impurities, but the energy of the emitted photons excludes the possibility of transitions involving shallow donors in the well. Similarly, we exclude the possibility of the ionization of shallow donors in the (Al,Ga)As barrier, where the electron binding energy on a shallow donor is larger than in GaAs.

In Ref. [19], terahertz emission is interpreted as resulting from recombination transitions between the electrical levels in a quantum well. In order to check whether the energy of 1.6 meV can be related to a separation of electrical levels of the heterostructure under study, we carry out self-consistent numerical calculations of the Schrödinger-Poisson equations of the band structure of the heterostructure for five values of the residual acceptor concentration N_A in the GaAs layer: 10^{14} cm^{-3}, 10^{15} cm^{-3}, 2×10^{15} cm^{-3}, 4×10^{15} cm^{-3}, and 8×10^{15} cm^{-3} (see Fig. 5). These values of N_A seem to be appropriate for a material of a high purity; however, it is difficult to say which of these five values is the closest to the true one. The differences between the second and the first electrical levels determined for N_A from the smallest to the largest value are, respectively, 10.7 meV, 23 meV, 28 meV, 36 meV, and 44 meV. It is clear that these values are much

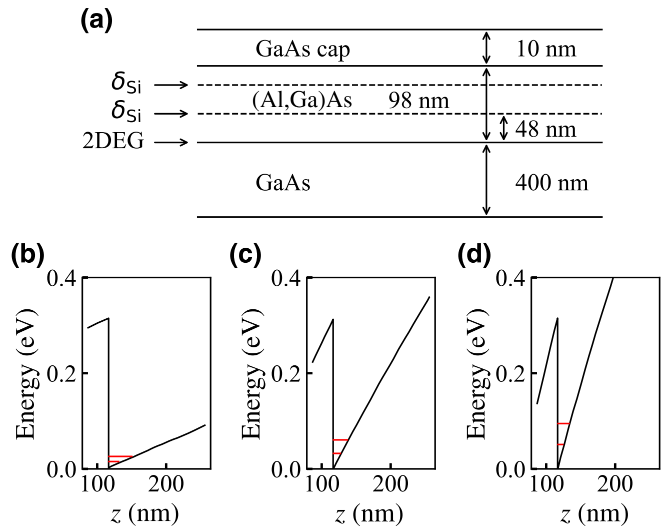

FIG. 5. (a) A schematic of the top layers of the heterostructure studied, including a GaAs channel, a (Al,Ga)As barrier with two δ-doping layers, and a GaAs cap layer. The separation of the δ layers is 30 mm. (b)–(d) The results of the self-consistent Schrödinger-Poisson calculations, showing the energy of the bottom of the conduction band in the region of the triangular quantum well for N_A equal to 10^{14} cm^{-3}, 2×10^{15} cm^{-3}, and 8×10^{15} cm^{-3} (b)–(d), respectively). The red horizontal bars show the energy of two lowest electron levels in the quantum well. The horizontal scale shows the distance to the top surface of the heterostructure.

higher than the energy of 1.6 meV; therefore, a relationship of the observed emission with radiative transitions between energy states in the quantum well can be excluded.

In our opinion, the mechanism of the observed emission can be traced back to Ref. [22], in which the Coulomb force of positively charged donors in a (Al,Ga)As barrier binding electrons in a GaAs quantum well is considered. It is shown that donors in the barrier can localize electrons in the quantum well and that the binding energy is not zero even at a considerable separation of these two entities. Figure 6 shows numerical results presented in Ref. [22] for the electron-donor binding energy as a function of the donor position with respect to the center of the well. In the case of the heterostructure studied in the present work, the distance of a Si donor layer from the GaAs/(Al,Ga)As interface is equal to 48 nm. This distance is typical for high-electron-mobility heterostructures, as it is appropriate to reduce the electron scattering by ionized donors in the barrier. However, the maximum distance of the separation of the donor from the well considered by the authors of Ref. [22] is only 25 nm. Nevertheless, Fig. 6 clearly shows that the binding energy decreases more and more slowly with an increasing distance of the donor from the quantum well and that at a distance of 25 nm from the interface, it is approximately equal to $(1/3)Ry^*$, which gives

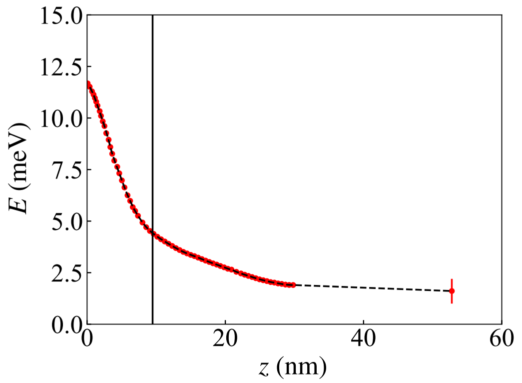

FIG. 6. The dependence of the binding energy of a donor on its position in a (Al,Ga)As/GaAs/(Al,Ga)As quantum well in the case of a finite potential barrier (0.318 eV) and a well width equal to 20 nm. The origin of the horizontal axis is in the middle of the quantum well. The thin vertical line shows the position of the GaAs/(Al,Ga)As interface. The red points from 0 nm to 30 nm are from Ref. [22]; a red point at 58 nm corresponds to the analysis presented in the present work. The error bar is equal to half of the full width at half maximum of the emission peak for sample S_1.

approximately 1.9 meV. A similar nature of the dependence of the electron binding energy in the well on ionized donors in the barrier is obtained in Ref. [23] for the case of $CdTe/Cd_{1-x}Mn_xTe$ structures. That work shows that in the case of a donor placed in a barrier at a distance of 10 nm from the interface, the binding energy is equal to approximately 4 meV. For comparison, for a donor placed at the center of the quantum well, the binding energy is 24 meV.

Experimentally, the presence of electrons localized in the well on positively charged impurities in the barrier has been shown in Ref. [24]. In that work, a $CdTe/Cd_{0.8}Mg_{0.2}Te$ quantum well is studied, in which the well and both barriers are homogeneously doped with iodine donors. On the basis of magnetoconductivity measurements over a wide frequency range of terahertz radiation, the authors show the presence of a quasicontinuum of localized energy states in the quantum well, generated by ionized donors in the barriers.

Based on these premises, we propose the following mechanism to be responsible for the emission of 1.6-meV radiation from the samples studied in this work. We assume that ionized Si donors in the barrier localize some electrons in the quantum well and that these electrons do not participate in the current at small bias. Under the influence of a sufficiently strong external electric field, these localized states are ionized and a jump of the current is observed. The emission results from recombination of electrons from the bottom of the first electrical state of the quantum well to barrier donor-related localized states in the quantum well. It is worth noting that in the case of a very well-defined distance of the donors in the barrier from the interface (48 nm), the spectrum of the observed emission should have a clearly marked maximum, in agreement with experimental observations. Strictly speaking, the (Al,Ga)As barrier contains two δ layers. In the analysis, we neglect the δ-layer which is closer to the top surface because of its large distance to the interface, equal to 78 nm. If we assume the binding energy of an electron on donors in the first barrier to be equal to 1.6 meV, we should expect a binding energy equal to $1.6 \times (48/78)^2 \approx 0.6$ meV, which is only about twice the value of the energy of thermal excitation in the experimental conditions (equal to about 0.3 meV at 4 K). For this reason, donors in the δ layer that is closer to the top surface of the heterostructure cannot effectively bind electrons in the quantum well.

V. CONCLUSIONS

In conclusion, we observe the emission of terahertz radiation from samples processed by electron-beam lithography on a high-electron-mobility $GaAs/Al_{0.36}Ga_{0.64}As$ heterostructure. A small energy of the emitted radiation, of 1.6 meV, allows us to propose that the emission originates from ionization-recombination transitions involving electrons in the GaAs quantum well, which are localized by ionized donors situated in the (Al,Ga)As barrier. A detailed literature search and the results of self-consistent calculations of energy levels in the heterostructure allow us to exclude emission mechanisms that have been invoked in the past to explain terahertz emission related to impurity ionization in quantum wells (i.e., transitions between impurity levels or between electrical levels of the quantum well). The relatively low power of the emitted radiation and the mechanism of emission precludes the application of such sources at room temperature. However, these can be valuable sources with which to carry out, calibrate, or check the operation of different types of bolometers operating at cryogenic temperatures. Such an application is crucial in astronomical observatory systems based on bolometers cooled to liquid-helium temperatures. The possibly small area of such a source, shown in the present paper, seems to be particularly attractive for such applications. Also, one can propose that by changing the distance of the dopants from the interface, the frequency of emitted photons can be increased up to a few terahertz.

ACKNOWLEDGMENTS

This research was partially supported by the Polish National Science Center Grants No. UMO-2017/27/N/ST7/01771 and No. UMO-2019/33/B/ST7/02858, by the Foundation for Polish Science through Grant No. TEAM/2016-3/25, and by the CENTERA Laboratories in the framework of the International Research Agendas Program for the Foundation for Polish Sciences, cofinanced by the European Union under the European Regional Development Fund (Grant No. MAB/2018/9).

[1] A. Maestrini, J. Ward, G. Chattopadhyay, E. Schlecht, and I. Mehdi, Terahertz sources based on frequency multiplication and their applications, J. RF-Eng. Telecommunications **62**, 118 (2008).

[2] K. Kasagi, S. Suzuki, and M. Asada, Large-scale array of resonant-tunneling-diode terahertz oscillators for high output power at 1 THz, J. Appl. Phys. **125**, 151601 (2019).

[3] A. Lisauskas, A. Ramer, M. Burakevic, S. Chevtchenko, V. Krozer, W. Heinrich, and H. G. Roskos, Terahertz emission from biased AlGaN/GaN high-electron-mobility transistors, J. Appl. Phys. **125**, 151614 (2019).

[4] I. Vurgaftman, R. Weih, M. Kamp, J. R. Meyer, C. L. Canedy, C. S. Kim, M. Kim, W. W. Bewley, C. D. Merritt, J. Abell, and S. Höfling, Interband cascade lasers, J. Phys. D: Appl. Phys. **48**, 123001 (2015).

[5] W. Knap, D. Dur, A. Raymond, C. Meny, J. Leotin, S. Huant, and B. Etienne, A far-infrared spectrometer based on cyclotron resonance emission sources, Rev. Sci. Instr. **63**, 3293 (1992).

[6] I. Melngailis, G. E. Stillman, J. O. Dimmock, and C. M. Wolfe, Far-Infrared Recombination Radiation from Impact-Ionized Shallow Donors in GaAs, Phys. Rev. Lett. **23**, 1111 (1969).

[7] S. R. Thomas and H. Y. Fan, Far-infrared recombination radiation from *n*-type Ge and GaAs, Phys. Rev. B **9**, 4295 (1974).

[8] W. D. Williams and H. Y. Fan, Stimulation of far-infrared emission produced by impact ionization in Ge(Sb), Appl. Phys. Lett. **36**, 400 (1980).

[9] A. V. Adrianov, A. O. Zakhar'in, Yu. L. Ivanov, and M. S. Kipa, Terahertz impurity luminescence under the interband photoexcitation of semiconductors, JETP Lett. **91**, 96 (2010).

[10] I. S. Makhov, V. Yu. Panevin, D. A. Firsov, L. E. Vorobjev, and G. V. Klimko, Impurity-assisted terahertz photoluminescence in compensated quantum wells, J. Appl. Phys. **126**, 175702 (2019).

[11] D. A. Firsov, V. A. Shalygin, V. Yu. Panevin, G. A. Melentyev, A. N. Sofronov, L. E. Vorobjev, A. V. Andrianov, A. O. Zakhar'in, V. S. Mikhrin, A. P. Vasil'ev, A. E. Zhukov, L. V. Gavrilenko, V. I. Gavrilenko, A. V. Antonov, and V. Ya. Aleshkin, Terahertz emission and photoconductivity in *n*-type GaAs/AlGaAs quantum wells: The role of resonant impurity states, Semiconductors **44**, 1394 (2010).

[12] D. A. Firsov, L. E. Vorobjev, V. Yu. Panevin, A. N. Sofronov, R. M. Balagula, I. S. Makhov, D. V. Kozlov, and A. P. Vasil'ev, Terahertz radiation associated with the impurity electron transition in quantum wells upon optical and electrical pumping, Semiconductors **49**, 28 (2015).

[13] S. Huant, M. Grynberg, G. Martinez, B. Etienne, B. Lambert, and A. Regreny, Magnetooptical studies of shallow donors in selectively doped GaAs/GaAlAs multiple quantum wells, Solid State Commun. **65**, 1467 (1988).

[14] K. Hirakawa, K. Yamanaka, M. Grayson, and D. C. Tsui, Far-infrared emission spectroscopy of hot two-dimensional plasmons in $Al_0.3Ga_0.7As$/GaAs heterojunctions, Appl. Phys. Lett. **67**, 2326 (1995).

[15] M. Białek, M. Czapkiewicz, J. Wróbel, V. Umansky, and J. Łusakowski, Plasmon dispersions in high electron mobility terahertz detectors, Appl. Phys. Lett. **104**, 263514 (2014).

[16] J. Łusakowski, R. Merten, and M. Grynberg, Magnetic field induced localization in semiinsulating GaAs, Acta Phys. Pol. A **82**, 551 (1992).

[17] J. Łusakowski, S. Huant, and M. Grynberg, Optical phonon assisted increase of impact ionization efficiency near the ultra quantum limit regime, Solid State Commun. **96**, 649 (1995).

[18] D. A. Firsov, L. E. Vorobjev, V. Yu. Panevin, A. N. Sofronov, R. M. Balagula, and D. V. Kozlov, Impurity-related terahertz emission from quantum well nanostructures, Lith. J. Phys. **54**, 46 (2014).

[19] S. D. Ganichev, S. N. Danilov, Ch. Gerl, D. A. Firsov, L. E. Vorobjev, V. A. Shalygin, V. Yu. Panevin, A. N. Sofronov, A. A. Andrianov, A. O. Zakhar'in, A. E. Zhukov, V. S. Mikhrin, and A. P. Vasil'ev, Intraband emission and absorption of terahertz radiation in GaAs/AlGaAs quantum wells, 2007 Joint 32nd International Conference on Infrared and Millimeter Waves and the 15th International Conference on Terahertz Electronics, 1–2 (2007).

[20] M. Helm, E. Colas, P. England, F. DeRosa, and S. J. Allen Jr., Observation of grating-induced intersubband emission from GaAs/AIGaAs superlattices, Appl. Phys. Lett. **53**, 1714 (1988).

[21] G. E. Stillman, David M. Larsen, C. M. Wolfe, and R. C. Brandt, Precision verification of effective mass theory for shallow donors in GaAs, Solid State Commun. **9**, 2245 (1971).

[22] K. Tanaka, M. Nagaoka, and T. Yamabe, Binding energy of the impurity level in the $Ga_1 - xAl_xAs$-GaAs-$Ga_1 - yAl_yAs$ superlattice, Phys. Rev. B **28**, 7068 (1983).

[23] M. P. Halsall, S. V. Railson, D. Wolverson, J. J. Davies, B. Lunn, and D. E. Ashenford, Spin-flip Raman scattering in CdTe/$Cd_1 - xMn_xTe$ multiple quantum wells: A model system for the study of electron-donor binding in semiconductor heterostructures, Phys. Rev. B **50**, 11755 (1994).

[24] M. Szot, K. Karpierz, J. Kossut, and M. Grynberg, FIR photon energy independent intra-impurity transitions in uniformly iodine-doped CdTe/$Cd_1 - xMg_xTe$ quantum well, Phys. Status Solidi C **0**, 609 (2003).