01.1;05.2;09.2;15.2

Resonances of relief triangular gratings for terahertz input/output in A_3B_5 semiconductors

© L.I. Gorai [1–4], N.A. Kostromin [1,2], A.S. Dashkov [1,2], A.D. Buravlev [1,3–5]

[1] St. Petersburg State Electrotechnical University „LETI“, St. Petersburg, Russia
[2] Alferov Federal State Budgetary Institution of Higher Education and Science Saint Petersburg National Research Academic University of the Russian Academy of Sciences, St. Petersburg, Russia
[3] Institute of Analytical Instrument Making, Russian Academy of Sciences, St. Petersburg, Russia
[4] AN HEO „University associated with IA EAEC“, Saint-Petersburg, Russia
[5] Ioffe Institute, St. Petersburg, Russia
E-mail: lig@pcgrate.com

Received May 20, 2024
Revised June 16, 2024
Accepted June 17, 2024

Diffraction efficiencies of relief semiconductor gratings in the terahertz range (THz) have been obtained by numerical modeling, and the properties of relief semiconductor gratings with a triangular symmetric profile of strokes have been considered. It is shown that three types of resonances are supported in such gratings: plasmon-polariton resonances (PPR), Rayleigh resonances, and resonances related to the stroke depth. The dielectric permittivity of InSb, GaAs and $Al_{0.3}Ga_{0.7}As$ at a given temperature was taken from literature data or calculations using the Drude−Lorentz model taking phonons into account. It is found that lattices of this type, unlike lattices with other stroke profiles, exhibit very deep and narrow PDP resonances, as well as Rayleigh resonances.

Keywords: terahertz range, A_3B_5 semiconductors, triangular diffraction gratings, plasmon-polariton resonance.

DOI: 10.61011/TPL.2024.10.60116.19999

The construction of terahertz (THz) radiation sources and receivers and, in particular, compact solid-state devices operating in this range is becoming increasingly relevant at present. Quantum-cascade lasers with their small dimensions, high efficiency, and the potential to design devices with the required output characteristics stand out among solid-state THz sources [1,2]. Super-multiperiod superlattices based on A_3B_5 materials constitute a different type of promising tunable THz radiation sources operating at room temperature. Intersubband optical transitions in them proceed between minibands in the conduction band (Wannier−Stark levels) and due to successive tunneling of carriers through several periods of the structure [3].

Relief surfaces (diffraction gratings and metamaterials supporting plasmon-polariton resonance (PPR) in TM polarization) are used to control THz radiation in semiconductor structures. At certain temperatures and doping levels, the semiconductor/dielectric interface (similar to the metal/dielectric interface in the visible range [4–6]) supports PPR in the THz range due to the interaction of light with oscillations of free electron gas in the semiconductor, provided that the wave vector of a surface plasmon is equal to the projection of the wave vector of a photon onto the interface with account for the diffraction grating vector (see below). Thus, all resonance effects known in optics may be reproduced in the THz range. Note that accurate numerical methods [7,8] and the Drude−Lorentz permittivity model [9] should be used in the study of these phenomena with gratings of different groove profiles. Note also that the technique for fabrication of short-wave gratings detailed in our recent study [10] is applicable in the IR and THz ranges and to group A_3B_5 semiconductors [11–13]. In other words, one needs to determine the design of gratings and control different types of resonances (PPR, Rayleigh (threshold) resonance, and resonance related to the groove depth) to manipulate THz radiation in semiconductor devices.

Note that the diffraction properties of relief gratings with a triangular groove profile in semiconductors have not been investigated yet. A symmetric field distribution along the groove is needed for efficient PPR. To clarify these issues, gratings based on InSb, GaAs, and AlGaAs with a symmetric triangular profile were examined in the present study, and several types of resonances, which are often located nearby and transform into one another [14], were investigated.

The PPR condition for diffraction order n of a grating with period d, wavelength λ of incident radiation in vacuum (TM polarization), and incidence angle θ is found from the approximate equality of the sum of wave vector projection $k\sin\theta$ and reciprocal grating vector $2\pi n/d$ to PPR wave vector magnitude $q_{\mathrm{SPP}} \cong k\sqrt{1+(\xi'')^2}$, where $k = 2\pi/\lambda$, $\varepsilon = \varepsilon' + i\varepsilon''$, $\xi = \sqrt{\frac{1}{\varepsilon}}$ — impedance, $|\xi| \ll 1$, $\xi'' < 0$, $\xi' > 0$ [7,14]. The propagation of a surface plasmon polariton is observed at $\theta = 24.76°$, $\lambda = 300\,\mu$m (1 THz, incidence from vacuum), and $n = 1$ in the first grating (with $\varepsilon = -66.6 + i27.1$) calculated for undoped InSb with account for the phonon interaction and $T = 300$ K. The possible $d = 513.9\,\mu$m value, which is determined from

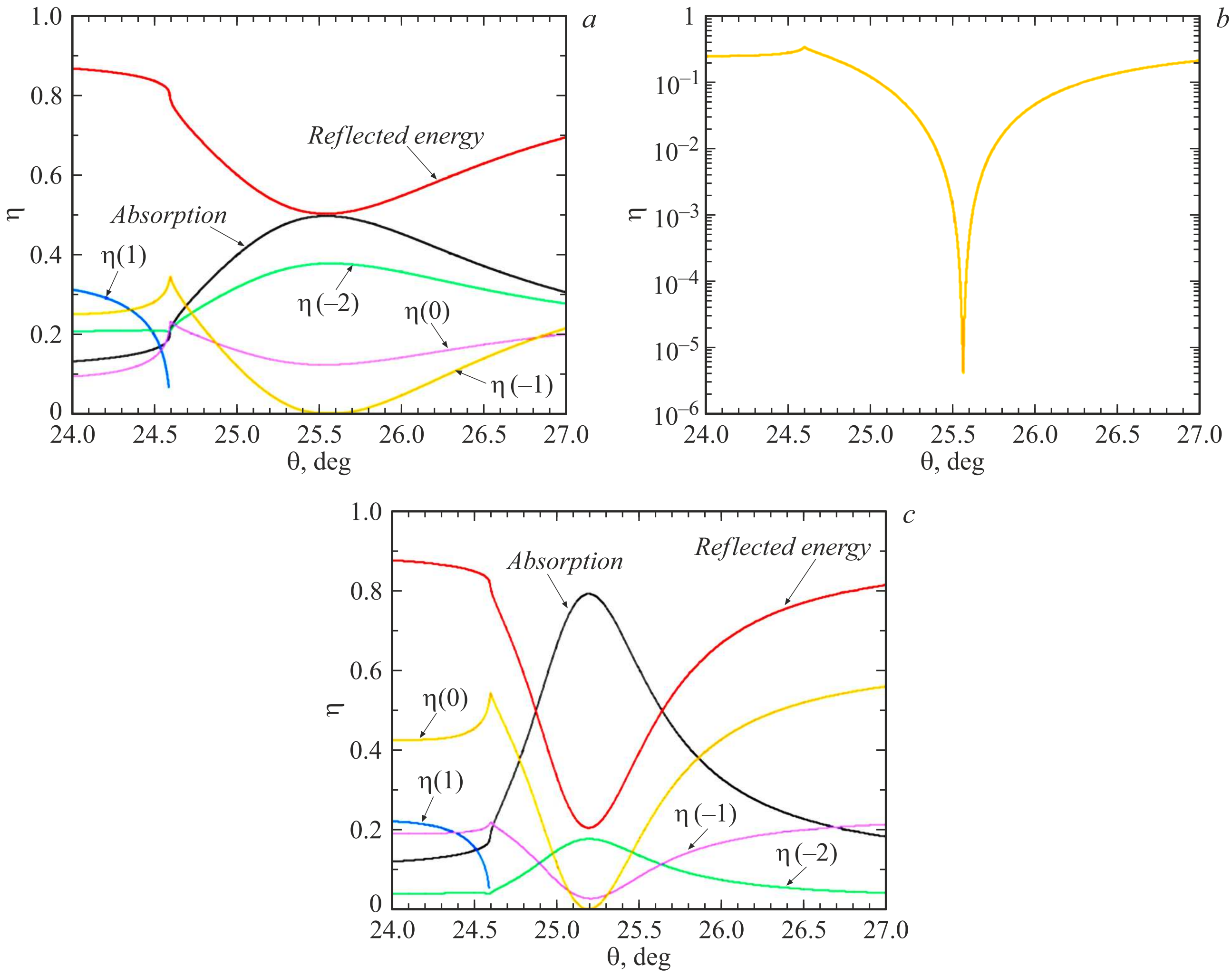

Figure 1. Absolute diffraction efficiency of orders (η) of the 1.946 mm^{-1} InSb grating with symmetric triangular grooves at a wavelength of 300 μm in TM polarization as a function of incidence angle θ. *a* — $\eta(n)$ for triangle angle $\alpha = 21.6^\circ$; *b* — $\eta(-1)$ in logarithmic scale for triangle angle $\alpha = 21.6^\circ$; and *c* — $\eta(n)$ for triangle angle $\alpha = 13.1^\circ$.

the grating equation, was taken from [5]. The corresponding Rayleigh resonance value for $n = 1$ is at $\theta = 24.6^\circ$. Therefore, taking into account the obtained ε value, one might expect the emergence of resonances of grating orders within the range of angles around $\theta = 25^\circ$. The angular dependences of absolute diffraction efficiency $\eta(n)$, absorption, and reflected energy were calculated using the PCGrate™ [15] software developed based on the rigorous boundary integral equation method (see Chapter 12 in [14]).

The simulation reveals a deep resonance at $\theta = 25.56^\circ$ (Fig. 1, *a*) for a symmetric triangular groove profile with angle $\alpha = 21.6^\circ$ governed by PPR (Fig. 1, *b*). The minimum of $\eta(-1) = 4.2 \cdot 10^{-6}$. The calculation accuracy was $\sim 0.001\%$ with 800 sampling points. The minimum of $\eta(0)$ and the maximum of absorption are observed beyond the Rayleigh threshold. However, the total reflected energy is large ($\sim 50\%$), since the $\eta(-2)$ and $\eta(0)$ values are high. The total reflected energy for the optimum sinusoidal grating may be several times smaller. No deep resonance in order -1 is found for an equivalent sinusoidal grating. Depth $h = 101.53\,\mu$m of the optimum triangular groove is more than 2 times greater than depth $h = 46.65\,\mu$m of the optimum sinusoidal profile. The angular distribution of η in the vicinity of PPR depends only weakly on the grating depth.

The simulation also reveals a deep resonance for InSb at $T = 300$ K with a minimum of $\eta(0) = 5.6 \cdot 10^{-6}$ at $\theta = 25.19^\circ$ and $\alpha = 13.1^\circ$ (Fig. 1, *c*). The reflected energy value for this resonance is several times smaller, which is attributable to the simultaneous minimization of $\eta(0)$ and $\eta(-1)$ and a modest value of $\eta(-2)$. One needs to use a grating with a smaller period to reduce the amount of reflected energy further.

The angular dependences of energy characteristics of the relief GaAs grating with doping level $N = 1 \cdot 10^{17}\,cm^{-3}$ at $T = 30$ K and $d = 1.7$ mm are presented in Fig. 2 for

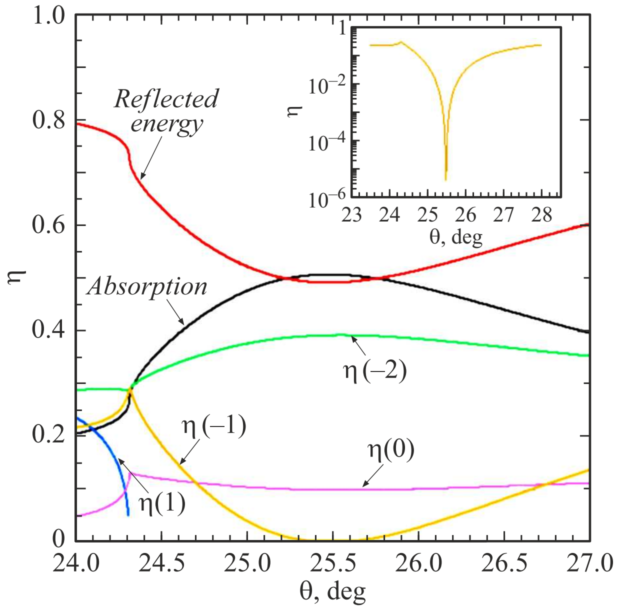

Figure 2. Absolute diffraction efficiency (η) of the 0.588 mm^{-1} GaAs grating with symmetric triangular grooves with angle 24.7° at a wavelength of 1000 μm in TM polarization at a temperature of 30 K as a function of incidence angle θ. The inset presents $\eta(-1)$ in logarithmic scale.

$\lambda = 1000\,\mu$m (0.3 THz). A very deep resonance with a minimum of $\eta(-1) = 3.5 \cdot 10^{-6}$ is observed at $\theta = 25.49°$ for a triangular groove with $\alpha = 24.7°$. The total reflected energy is large ($\sim$ 50%), since the $\eta(-2)$ and $\eta(0)$ values are high. No deep resonance in order -1 is found for an equivalent sinusoidal grating. The optimum triangular profile is approximately 2 times deeper than the optimum sinusoidal profile. The angular and spectral position of $\eta(-1)$ depends only weakly on the grating depth.

The $Al_{0.3}Ga_{0.7}As$ grating with doping level $N = 1 \cdot 10^{18}\,\text{cm}^{-3}$ at $T = 30$ K operating at the same frequency as the one examined in the previous case was the last to be modeled. A deep resonance with a minimum of $\eta(-1) = 2.7 \cdot 10^{-6}$ is observed for a triangular groove profile with $\alpha = 18.3°$ at incidence angle $\theta = 23.69°$ (Fig. 3, *a*). This resonance is a combination of the Rayleigh resonance and PPR. The angular and spectral position of $\eta(-1)$ depends only weakly on the grating depth. A deep resonance in order -1 is not observed in the equivalent model of a perfectly conducting grating (i.e., without PPR); only the Rayleigh resonance with a minimum of $\eta(-1) = 0.027$ is present (Fig. 3, *b*).

Thus, the diffraction properties of relief A_3B_5 semiconductor gratings with a symmetric triangular groove profile supporting three types of resonances (PPR, Rayleigh resonance, and resonance related to the optimum groove depth) have been examined for the first time. Such gratings feature very deep and narrow PPR and Rayleigh resonances and broad optimum-depth resonances. These resonances are often located nearby and transform into one another, which should be taken into account in the design of THz radiation sources and receivers.

Funding

This study was supported by the Ministry of Education and Science of the Russian Federation (№ 75-01438-22-06, FSEE-2022-0018).

Conflict of interest

The authors declare that they have no conflict of interest.

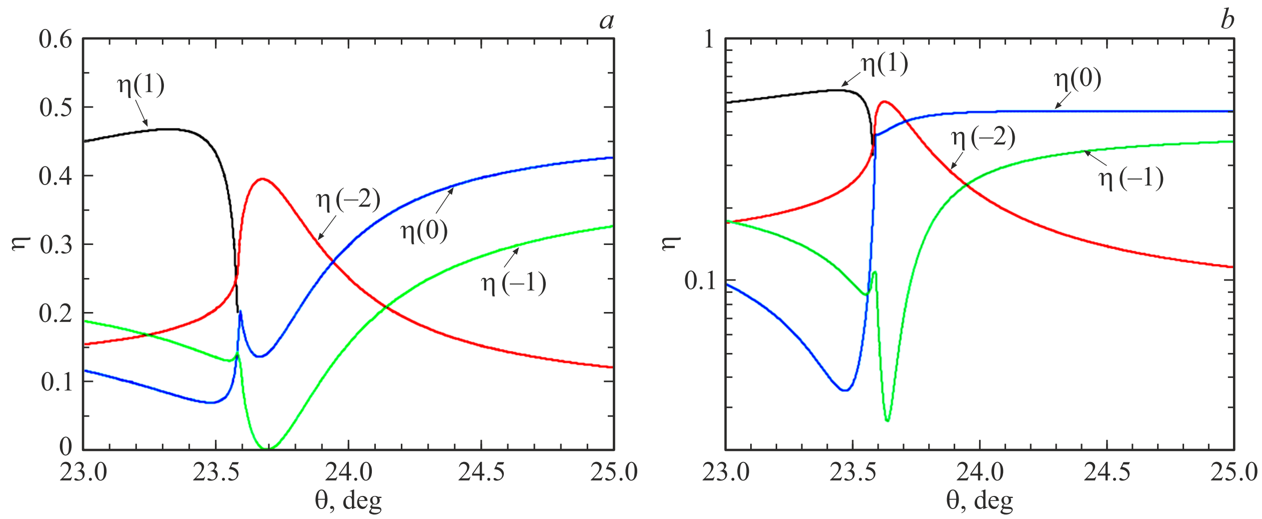

Figure 3. *a* — Absolute diffraction efficiency (η) of the 0.6 mm^{-1} $Al_{0.3}Ga_{0.7}As$ grating with symmetric triangular grooves with an angle of 18.3° at a wavelength of 1000 μm in TM polarization at a temperature of 30 K as a function of incidence angle θ; *b* — $\eta(n)$ of the same grating, but with a perfect conductivity.

References

[1] A. Khalatpour, A.K. Paulsen, C. Deimert, Z.R. Wasilewski, Q. Hu, Nat. Photon., **15** (1), 16 (2020). DOI: 10.1038/s41566-020-00707-5

[2] T.A. Bagaev, M.A. Ladugin, A.A. Marmalyuk, A.I. Danilov, D.V. Ushakov, A.A. Afonenko, A.A. Zaytsev, K.V. Maremyanin, S.V. Morozov, V.I. Gavrilenko, R.R. Galiev, A.Yu. Pavlov, S.S. Pushkarev, D.S. Ponomarev, R.A. Khabibullin, Tech. Phys. Lett., **48** (5), 45 (2022). DOI: 10.21883/TPL.2022.05.53479.19162.

[3] A.S. Dashkov, S.A. Khakhulin, D.A. Shapran, G.F. Glinskii, N.A. Kostromin, A.L. Vasiliev, S.N. Yakunin, O.S. Komkov, E.V. Pirogov, M.S. Sobolev, L.I. Goray, A.D. Bouravleuv, J. Semicond., **45** (2), 022901 (2024). DOI: 10.1088/1674-4926/45/2/022701

[4] R. Parthasarathy, A. Bykhovski, B. Gelmont, T. Globus, N. Swami, D. Woolard, Phys. Rev. Lett., **98** (15), 153906 (2007). DOI: 10.1103/PhysRevLett.98.153906

[5] N.A. Balakhonova, A.V. Kats, V.K. Gavrikov, Appl. Phys. Lett., **91** (11), 113102 (2007). DOI: 10.1063/1.2783183

[6] M. Kuttge, H. Kurz, J.G. Rivas, J.A. Sánchez-Gil, P.H. Bolívar, J. Appl. Phys., **101** (2), 023707 (2007). DOI: 10.1063/1.2409895

[7] I.S. Spevak, M.A. Timchenko, V.K. Gavrikov, V.M. Shulga, J. Feng, H.B. Sun, A.V. Kats, Appl. Phys. B, **104** (4), 925 (2011). DOI: 10.1007/s00340-011-4575-3

[8] J. Tong, F. Suo, T. Zhang, Z. Huang, J. Chu, D.H. Zhang, Light Sci. Appl., **10** (1), 58 (2021). DOI: 10.1038/s41377-021-00505-w

[9] J.S. Blakemore, J. Appl. Phys., **53** (10), R123 (1982). DOI: 10.1063/1.331665

[10] L.I. Goray, T.N. Berezovskaya, D.V. Mokhov, V.A. Sharov, K.Yu. Shubina, E.V. Pirogov, A.S. Dashkov, Tech. Phys., **67** (13), 2097 (2022). DOI: 10.21883/TP.2022.13.52229.81-21.

[11] J.P. Marsh, D.J. Mar, D.T. Jaffe, Appl. Opt., **46** (17), 3400 (2007). DOI: 10.1364/AO.46.003400

[12] S. Zha, D. Li, Q. Wen, Y. Zhou, H. Zhang, Micromachines, **13** (7), 1000 (2022). DOI: 10.3390/mi13071000

[13] B.V. Egorov, S.Yu. Karpov, M.N. Mizerov, E.L. Portnoi, V.B. Smirnitskii, Zh. Tekh. Fiz., **54** (10), 1948 (1984) (in Russian). https://www.mathnet.ru/php/archive.phtml?wshow =paper&jrnid=jtf&paperid=2001&option_lang=rus

[14] T. Antonakakis, F.I. Baida, A. Belkhir, K. Cherednichenko, S. Cooper, R. Craster, G. Demésy, J. Desanto, G. Granet, B. Gralak, L. Goray, L. Li, D. Maystre, B. Stout, F. Zolla, G. Schmidt, E. Skeleton, S. Guenneau, A. Nicolet, E. Popov, B. Vial, *Gratings: theory and numerical applications* (Universitaires de Provence, Marseille, 2014). https://hal.science/hal-00785737

[15] *International Intellectual Group, Inc.* [Electronic source]. www.pcgrate.com

Translated by EgoTranslating