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BRIDGING THE TERAHERTZ GAP USING SOLID-STATE DEVICES

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Terahertz (THz) frequencies nestled between the microwave and infrared ranges in the electromagnetic spectrum radiation remain one of the most attractive research topics. A particular attention is given to the issues related to the development of solid-state-based room-temperature high-power, stable and portable terahertz emitters and detectors as well as user-friendly THz imaging and spectroscopy. At the dawn of this research, four decades ago, academician Juras Požela [J. Požela and V. Jucienė, *Physics of High-Speed Transistors* (Vilnius, Mokslas, 1985)] considered possible physical mechanisms – hot electrons, plasma effects, Josephson junctions, masers, etc. – that can successfully be employed to cover the THz frequencies using solid-state physics approaches. In this work, we briefly overview the recent achievements and advances illustrating an incredibly high precision of the scientific predictions given by Acad. Juras Požela based on his wide erudition, deeply sensitive intuition and great insights, gifted feeling of scientific trends and evolution. The paper presents a structured snapshot of the modern devices with highlights in their physics behind the operation and main parameters and includes contemporary topics in THz science and technology related to electrically pumped GaN-based sources and quantum semiconductor structures such as resonant tunnelling diodes, quantum cascade lasers, and quantum semiconductor superlattices. Possible challenges in further development of the described approaches and devices are illuminated.

Keywords: terahertz, hot electrons, Gunn effect, plasma waves, field-effect transistors, thermal emitters, quantum structures, Josephson junctions

1. Introduction

Academician Juras Požela played a pivotal role in the establishment of semiconductor research, the development of semiconductor technology and in stimulating microelectronics industry in Lithuania. The initiated semiconductor research was mainly focused on hot electron-related effects, plasma phenomena and current instabilities as well as advancement of fast electronic devices. The research activities gained a broad interest worldwide allowing him, therefore, to establish Semiconductor Physics Institute which was one of the internationally leading institutions in hot electron physics in that time. Academician inspired the installation of technological infrastructure, encouraged the systematic scientific investigation approach, which covered materials growth, their characterization, and further implementation into novel high-frequency devices. Despite a deep focus on the semiconductor research in the microwave range, his versality and scientific curiosity were extended into a much wider interest scale. A particular attention was dedicated to the terahertz (THz) frequency range (1 THz is 10^{12} Hz), which is settled between the microwaves and infrared ranges in the electromagnetic spectrum and in which no solid state-based devices were available at that time. The reason was defined by the specific place of the THz range in the electromagnetic radiation scale – from the ‘red’ side of the spectrum, device operation is mainly limited by the cut-off frequency due to the carrier transit time or parasitic RC time constants. In contrast, from a ‘blue’ wing of the spectrum, the operation range is defined by an energy band gap of semiconductor or quantum levels in artificially designed and fabricated nanostructures. As THz quantum is relatively small (1 THz is 4.1 meV), it is challenging to implement these principles for room temperature operating gadgets. Therefore, design of devices in the THz range requires innovative scientific approaches and the confluence of different technological concepts aiming to ‘bridge’ the THz range.

Four decades ago, in 1985, Acad. Juras Požela and Dr. Vida Jucienė published a compelling book entitled *Physics of High-Speed Transistors* [1] dedicated to the consideration of possible physical mechanisms aiming to increase the operation speed of solid-state devices which can further serve as components of novel integrated circuits. An illustrative sketch of feasible mechanisms is given in Fig. 1. As seen there, hot electrons, plasma effects, Josephson junctions, impact ionization, negative effective mass effect, and masers are indicated as possible physical mechanisms to be employed in the generation of THz frequencies using solid-state physics approaches. As shown in Fig. 1, the main considerations were centred on the ‘red wing’ of the spectrum, discussing mainly the scale up to 1 THz, while the remainder part – from 1 to 10 THz – received much less attention. At that time, eight years were still needed to discover ‘shallow water type’ plasma instabilities in two-dimensional (2D) channels [2], whereas nine years were still remaining until the invention of the infrared quantum cascade laser [3], and 17 years were needed to develop it in the THz range [4]. Those studies enabled breakthroughs to cover nearly all the THz range using semiconductor structures. Moreover, it showed optimistic tracts to reduce the dimensions of THz systems and revealed their performances at room temperature, which is essentially important for a user-friendly design and convenience for their further implementation in the real operating environment.

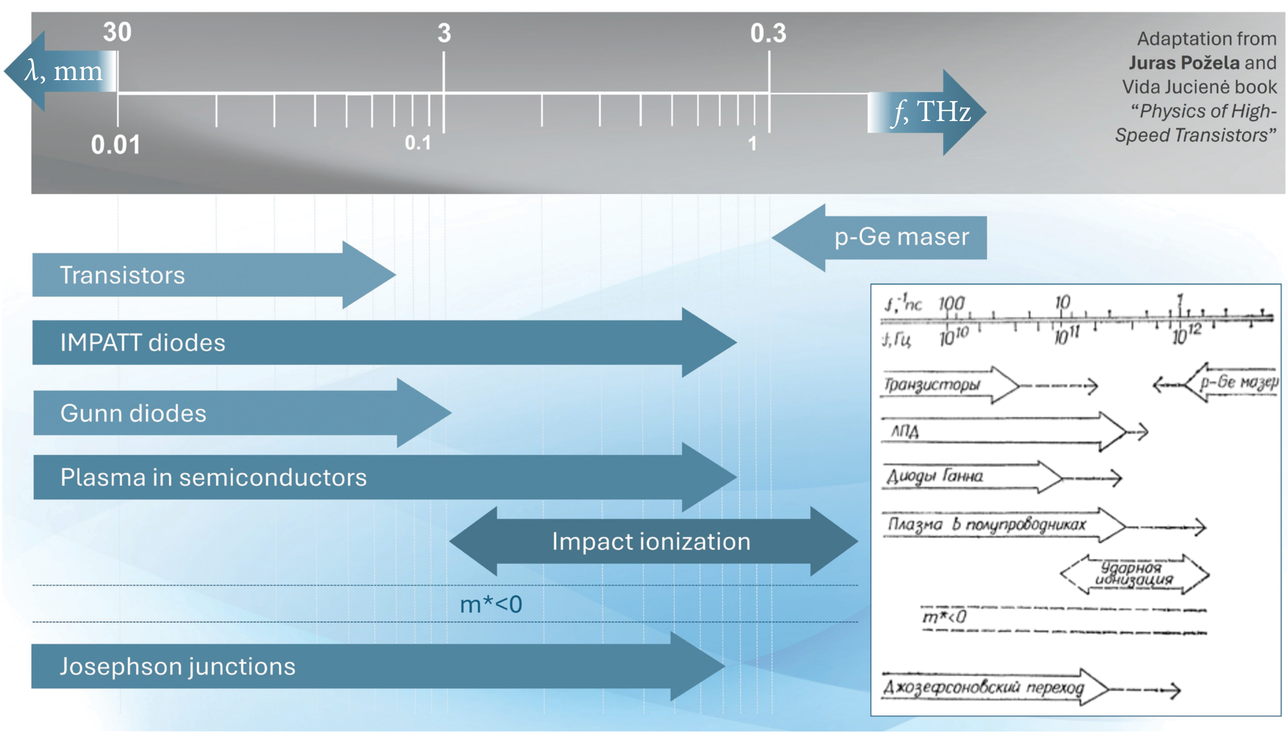

Fig. 1. Illustration of the bridging the terahertz gap via different physical effects in the solid state. The left panel is adapted from the book entitled *Physics of High-Speed Transistors* by Academician Juras Požela and Dr. Vida Jucienė (Vilnius, Mokslas, 1985) [in Russian]. The right panel is an original sketch of the figure reprinted from the aforementioned book.

In this paper, we briefly review recent achievements and advances in bridging the THz gap via solid-state approaches hence illustrating the incredibly high precision of the scientific forecast given by Acad. Juras Požela based on his wide erudition, deeply sensitive intuition and great insights, gifted feeling of scientific trends and evolution. The paper is organized as follows. Section 2 provides description of predicted trends in evolution of high-speed devices given by Acad. Juras Požela, giving main attention to hot-electron related effects, plasma wave induced phenomena, Landau level lasers, and Josephson junctions. Section 3 is dedicated to concepts and devices what was beyond the predictions: it describes recent advances in frequency multipliers and thermal emitters; special emphasis is given to electrically pumped THz emitters employing GaN structures, and THz devices based on semiconductor quantum structures such as resonant tunneling diodes, quantum cascade lasers and superlattices. Finally, in Conclusions, the presented concepts and devices are graphically summarized indicating remaining challenges and possible insights on scientific topic within the field.

2. Predicted trends in evolution of high-speed devices

2.1. Hot electron effects for THz frequencies

Under application of a strong electric field, electrons in semiconductors can gain a significant excess of energy that can be much higher than the lattice one. These effects serve as an attractive background to generate high-frequency radiation and can be implemented in electronic devices. In what follows, we have focused ourselves on impact-ionization-avalanche-transit-time (IMPATT) diodes, Gunn diodes, and added the bow-tie diodes concept for THz detection as they rely on hot electron effects in the solid state.

IMPATT diodes usually demonstrate superior power properties and operate up to millimetre-wave frequencies, showing a significant potential for applications in the THz region [5].

A schematic diagram of the IMPATT diode is given in Fig. 2. In the reverse bias regime, avalanche breakdown occurs in the Avalanche region. A confined bunch of carriers is generated in a narrow region and its transit through a depleted drift

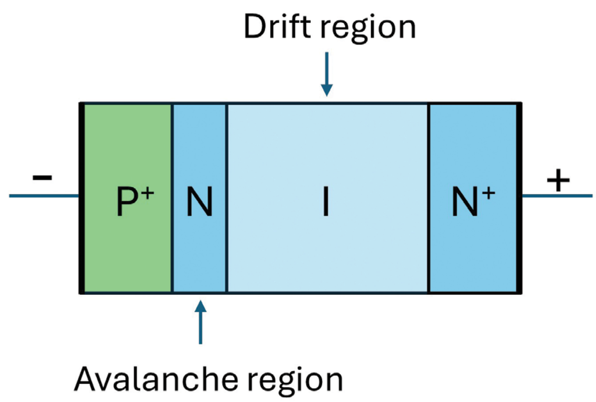

Fig. 2. Schematic diagram of the single-drift-region of an IMPATT diode.

region induces a current flow in the outer circuit. The avalanche formation time and the drift time are in the π phase delay of the current with respect to the voltage, resulting in a negative high-frequency dynamic resistance, and the generation of RF power is in the milliwatt level at hundreds of gigahertz. The first research and development efforts of IMPATT diodes were made in the late 1970's and 1980's with the subsequent improvement of fabrication technologies and search for more sophisticated doping profiles to improve dc-to-RF conversion efficiency as well as RF output power [6].

The instability of the current is caused by the impact ionization lagging the electric field. As it follows from the linear theory, RF oscillation frequency can be increased in materials with a high impact ionization rate and a small ionization delay time. Acad. J. Požela has developed a theoretical model to find the delay time and investigate the impact ionization evolution stages [7]. When a high electric field is applied, tiny domains of enhanced impact ionization, called microplasmas, appear at the dislocations and current exhibits the typical features of noise. Acad. J. Požela together with his team revealed that the microwave field applied to the avalanche diode in addition to the dc bias leads to a considerable increase of microwave noise power in Si- and GaAs-based avalanche diodes [8].

Gallium nitride, with its high breakdown voltage and electron saturation velocity, has been recognized as one of the most promising materials for the fabrication of IMPATT diodes. Application of GaN materials has made it possible to extend the operating frequency of IMPATT to the THz band [9].

AlGaN/GaN heterojunctions can induce a high density of two-dimensional electron gas (2DEG) at the interface with a high electron mobility, where the electron saturation drift velocity is higher than that of bulk GaN. AlGaN/GaN structures can operate in the IMPATT mode when avalanche breakdown occurs in the conducting channel. The bilateral IMPATT diode based on the AlGaN/GaN heterostructure with 2DEG demonstrates a wide operating frequency band up to 0.9 THz with the maximum dc-RF conversion efficiency above 17% and the maximal power of 3.18 W/mm around 420 GHz [10].

GaN structures are promising materials for the fabrication of Gunn-effect based devices enabling them to reach THz frequencies. GaN semiconductor displays several attractive properties – a high electrical strength, which is related to its large energy gap, a high peak and saturation velocity, as well as its low relaxations times as compared with other III–V materials typically used in Gunn diodes – making it a promising candidate for the development and applications in this field [11]. It is worth noting a detailed theoretical study of GaN-based planar asymmetric nanodiodes as promising devices for the fabrication of room temperature THz Gunn oscillators enabling them to reach 400 GHz frequencies [12]. GaN-based Gunn diodes with side-contact and field plate technologies were fabricated, thus enabling a stable working regime due to a good passivation as protection from electro-migration and ionization between the electrodes, as well as a better heat sink to the GaN substrate and large side contacts. The device operation range extended up to the 0.3–0.4 THz range with reliable characteristics [13].

Hot electron effects can successfully be applied for broadband THz detection at room temperature. One of interesting concepts that originated at the Semiconductor Physics Institute is the so-called bigradient effect [14, 15]. It was demonstrated that even if a uniform semiconductor with an asymmetrically shaped geometry is placed in a strong electric field, its current–voltage characteristics expose asymmetry, and therefore, it can be employed to detect high-frequency radiation. It was revealed that physics behind the effect is a non-uniform carrier heating in an asymmetrically-shaped structure. The ability for room temperature broadband GHz–THz sensing was initially demonstrated in GaAs bow-tie planar diodes containing the n-n$^+$ junction [16]. As carrier heating is proportional to the carrier mobility, InGaAs-based structures were chosen for further development of bow-tie sensing devices. Merging the non-uniform carrier heating in a semiconductor and bow-tie antenna properties in a single device allowed one to increase the sensitivity up to 10 V/W, and to demonstrate the broadband room-temperature operation up to 2.5 THz [17] and to implement it for spectroscopic THz imaging [18, 19]. Optimization of the structures enabled better performances in the subTHz range [20], fast THz detection up to 6 ns response time [21], and coherent THz imaging [22]. GaN-based bow-tie diodes revealed broadband room-temperature performances in the subTHz range with a sensitivity of 4 V/W [23].

These devices can be produced using planar technology, they are also reliable, broadband and fast, and hence can be employed as an essential component for the development of a compact THz imaging system. An important step towards this direction is the integration of the devices with diffractive optics components enabling hence reduction of the dimension of the THz system and the user-friendly approach.

A promising approach to achieving this involves the integration of diffractive optical elements directly onto the detector chip, thus enabling compact and efficient THz sensing platforms [24]. As an illustration, further we describe a single-sided integration of Fresnel zone plates (ZPs) with InGaAs bow-tie diodes on a semi-insulating InP substrate.

Initially, numerical simulations using finite integration and finite-difference time-domain methods were performed to allow a detailed understanding of the electromagnetic field distribution in the integrated THz detector system. As a point of departure, modelling of the standalone bow-tie antenna on a 335-μm-thick InP substrate – without symmetry constraints due to the detector's geometry – revealed that the electric field concentrates effectively at the active region. Specifically, the electric field strength at the InGaAs–gold contact point reaches 12.4 V/m, whereas a secondary peak of 17.6 V/m occurs outside the active area and does not affect carrier heating. Integration of a Fresnel zone plate around the bow-tie antenna enables a significant increase of the electric field reaching 77.6 V/m with a maximum of 108 V/m outside the detector zone. When contact tracks were added to the bow-tie structure and the first Fresnel zone was separated (as shown in Fig. 3), the peak electric field at the active contact region reached 70.8 V/m under 600 GHz illumination. Although this represents a ~9% reduction compared to the ZP- bow-tie system without contacts – primarily due to the impedance mismatch introduced by the metal tracks – it still constitutes a 5.7-fold enhancement over the standalone bow-tie antenna. These results underscore the cumulative effect of each design element – antenna geometry, diffractive focusing, and contact layout – on optimizing the local field enhancement and, consequently, the detector's sensitivity.

The obtained results demonstrate the cumulative effect of diffractive optics and contact design on enhancing the electric field strength and improving the detector performance. Moreover, it allows one to generate THz structured light [25] or apply its angular momentum for enhanced THz imaging [26]. It is worth noting that the non-paraxial approach needs to be used in the compact design of optical components [27].

2.2. Nanometric transistors for THz frequencies – plasma waves, instabilities, and resistive mixing

The modern understanding of plasma-wave phenomena in electronic devices utilizing 2DEGs emerged only in the mid-1980s, following the development of modulation-doped GaAs/AlGaAs heterostructures [28]. Years before, Acad. Juras Požela had contributed to this field by establishing key concepts of hydrodynamic and plasma-wave transport in semiconductors [29]. As device dimensions shrank into the sub-micron regime and high-mobility channels became available in III–V heterostructures and nanoscale CMOS processes, those early ideas found a natural continuation: the same hydrodynamic electron-fluid description underpins the excitation of plasma waves in nanometric transistors at THz frequencies. In this sense, modern THz plasmonic field-effect transistor (FET) detectors can be viewed as the technological realization of physical principles that Acad.

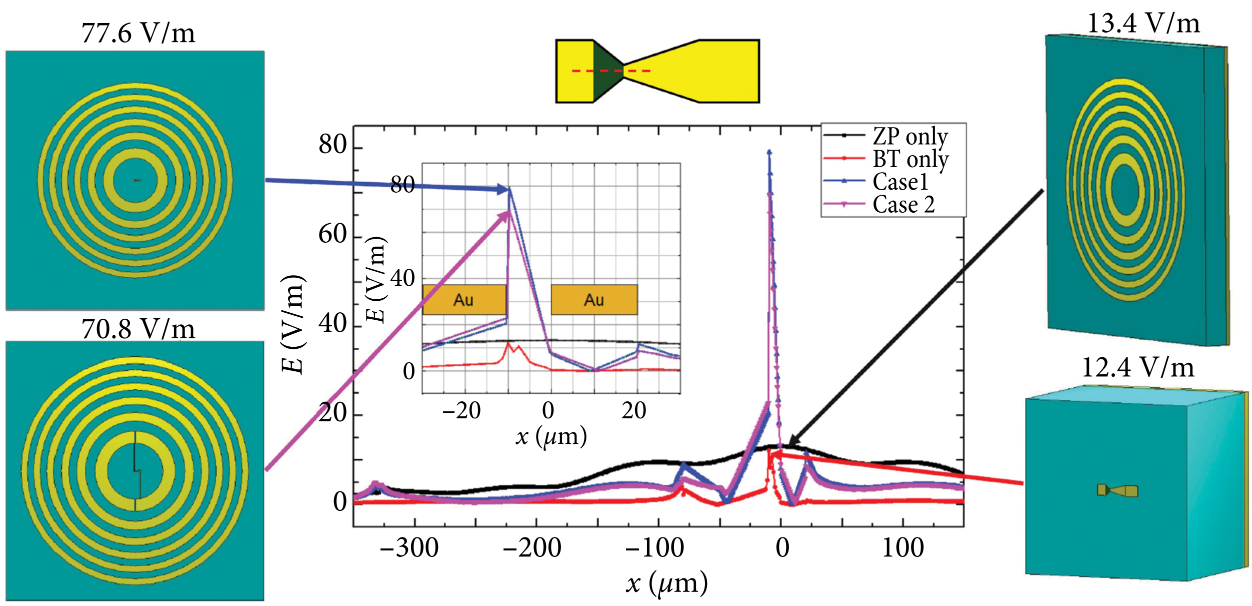

Fig. 3. Simulated electric field distribution for four THz detector configurations under 600 GHz illumination: ZP only (black curve, 13.4 V/m), bow-tie only (red curve, 12.4 V/m), Case 1: bow tie with an integrated Fresnel zone plate (blue curve, 77.6 V/m) and Case 2: bow tie with ZP plus contact tracks and a separated first zone (magenta curve, 70.8 V/m). The central plot shows the electric field intensity along the x axis for all cases, with the inset highlighting field localization at the Au contact region.

J. Požela's school had conceptually formulated decades earlier.

A crucial intermediate step between fundamental plasmon physics and THz device functionality was the study of patterned 2DEG structures at cryogenic temperatures. Experiments on grating-gate and mesa-defined GaAs/AlGaAs heterostructures conducted by Allen et al. [30] provided the first evidence of standing plasmonic charge-density waves in 2DEGs driven by sub-millimetre-wave excitation. Transmission and reflection spectroscopy revealed discrete plasmon resonances whose frequencies followed the expected $\sqrt{n_s / L}$ -scaling with carrier density and channel length. Those results confirmed that incident THz radiation can efficiently excite collective electron oscillations in confined 2D channels and that device geometry defines the spatial pattern of the plasmonic modes.

As fabrication techniques improved, the photoresponse of 2DEG structures gained scientific attention due to the nonlinear rectification of the plasmonic field. That transition linking plasmonic excitation to an electrical output became a key enabling step toward compact, room-temperature THz imaging systems, in which FET-based sensors were identified as promising solid-state detector candidates [31].

The theoretical unification of photoresponse observations was provided by the Dyakonov–Shur (DS) model, initially introduced for plasma instabilities [2] and later elaborated in its detection-oriented formulation in 1996 [32]. In this model, the FET channel acts as a transmission-line cavity whose source and drain boundary conditions determine whether standing or travelling electron-density waves are formed. Two regimes naturally arise: a resonant regime, where well-defined plasma modes appear in short, high-mobility channels; and an overdamped regime, dominant at room temperature, in which plasma oscillations decay within a single cycle yet still modulate the channel conductivity. In the overdamped limit, the hydrodynamic DS model becomes mathematically equivalent to resistive self-mixing, where the THz-induced gate–channel voltage is rectified by the distributed array of transistors with nonlinear current–voltage characteristics [33], and that was later systematically analysed in the sensitivity study covering a variety of device concepts and material systems [34].

With these foundations established, nanometric transistors rapidly evolved from conceptual plasmonic structures to practical THz detectors. A key milestone for large-area room-temperature THz imaging was reached with the implementation of 1-k-pixel CMOS THz cameras operating in the 0.7–1.1 THz range, demonstrated by Pfeiffer and colleagues in 65-nm CMOS technology [35]. More recently, Holstein et al. (2024) have reported a fully integrated 8 × 8 patch-antenna-coupled TeraFET array optimized for 3.4 THz quantum-cascade-laser illumination, validating CMOS-compatible TeraFETs as scalable THz detector modules [36]. Across CMOS, GaN/AlGaN HEMTs, and InGaAs-based platforms, the detection mechanism remains unified: plasmon-assisted nonlinear rectification in nanoscale-gated channels [34]. This convergence underlies the emergence of compact, room-temperature THz imagers and spectrometers based on solid-state transistor technology [31].

The physical picture has been fully confirmed only recently through the direct near-field visualization of THz plasma waves in operating FET detectors. Using scattering-type THz nano-imaging, Soltani et al. achieved the direct nanoscopic observation of plasma waves in the channel of a graphene field-effect transistor, revealing a propagating-wave pattern with a deep-subwavelength spatial resolution [37]. Those measurements were performed at room temperature conditions and verified the central assumption of DS-type and self-mixing models – incident THz radiation launches collective electron oscillations whose nonlinear interaction with the channel transport yields the measurable dc photoresponse. Three decades of theoretical development, spectroscopic investigation, and nanoscale device engineering have thus converged into a unified, experimentally validated description of THz detection in nanometric transistors.

It is worth noting that the use of large area GaAs field effect transistors enables THz detection up to 22 THz at room temperature [38].

This matured framework now also opens a path toward plasma-wave THz sources, where controlled instabilities or gain in nanoscale electron fluids may enable compact emitters, which are strongly conceptually linked to the early studies of plasma instabilities pursued by Acad. J. Požela and his colleagues.

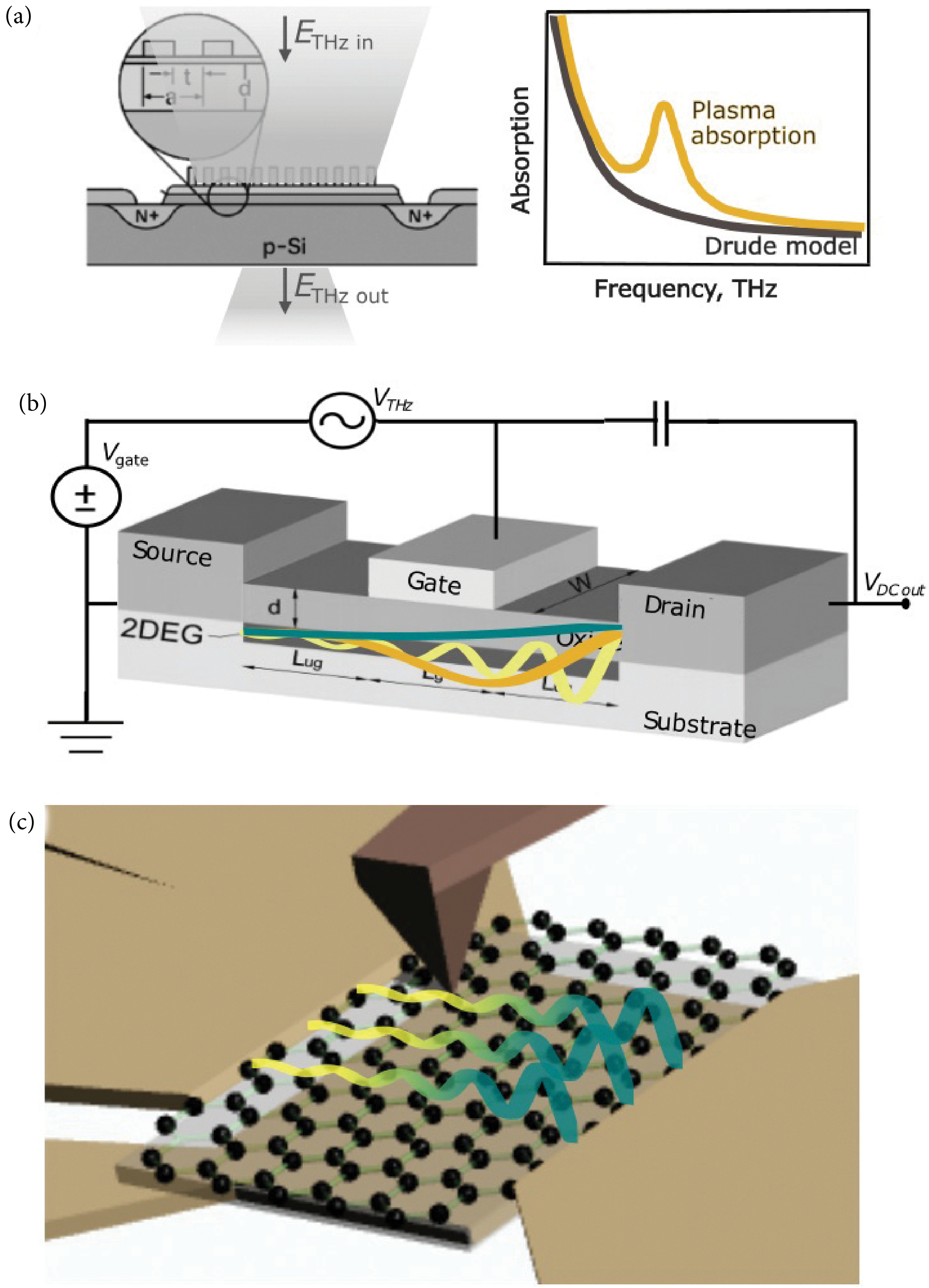

Fig. 4. Schematic illustration of the evolution from early hydrodynamic plasma-wave models to modern THz plasmonic FETs. (a) Left panel: patterned 2DEG structures in GaAs/AlGaAs heterostructures enabling observation of standing plasmonic waves at cryogenic temperatures. Right panel: transition from spectroscopic plasmon measurements to photovoltage generation via nonlinear rectification. (b) Dyakonov–Shur model describing resonant and overdamped plasma-wave regimes in nanoscale channels. (c) Near-field imaging of propagating plasma waves confirming the physical origin of the THz photoresponse.

2.3. Landau level lasers

In semiconductors, there is a large variety of fundamental excitations whose energies can be continuously tuned over a wide range of THz frequencies by applied external fields. Landau level emitters are quantum devices that exploit the discrete energy levels formed when charge carriers – electrons or holes – move under a strong perpendicular magnetic field. In such systems, the continuous electronic energy spectrum becomes quantized into Landau levels.

Landau level separation is directly proportional to magnetic field and inversely proportional to the effective mass of the carriers. In semiconductors with small effective carrier masses, the level splitting can be varied over the whole THz frequency range with moderate magnetic fields of the order of a few teslas. By tuning the magnetic field, one can continuously tune the emission frequency.

Landau levels are the solution of the Schrödinger equation. With magnetic field in the direction of the z axis, the resulting eigenvalues ε_{n,k_z} are given as

$$\varepsilon_{n,k_z} = \hbar\omega_c\left(n+\frac{1}{2}\right)+\frac{\hbar^2 k_z^2}{2m^*}, \quad n = 0, 1, 2, ...$$

where the first term represents Landau quantization in the plane perpendicular to magnetic field, and the second term is free-electron motion along the magnetic field without quantization, here the cyclotron frequency $\omega_c = eB/m^*$, B is the magnetic field, m^* is the effective mass, and $\hbar k_z$ is the electron momentum in the direction of the magnetic field.

Several Landau sub-bands are shown in Fig. 5 for the magnetic field in the direction of the z axis. According to the selection rules, only vertical transitions with $\Delta n = 1$ are allowed. The emitted radiation is circularly polarized in the direction of the z axis.

A Landau level laser was first proposed in the late 1950s by Schneider [39] who suggested a maser in the microwave range by stimulated emission of relativistic electrons. Wolff [40] proposed a tunable terahertz laser based on radiative transitions between Landau levels in narrow-gap semiconductors.

The first experimental observation of spontaneous far-infrared radiation due to transitions of carriers between Landau levels in n-InSb was reported by Gornik in 1972 [41] – transitions of electrically excited electrons between the Landau levels resulted in emission powers of the order of several nanowatts.

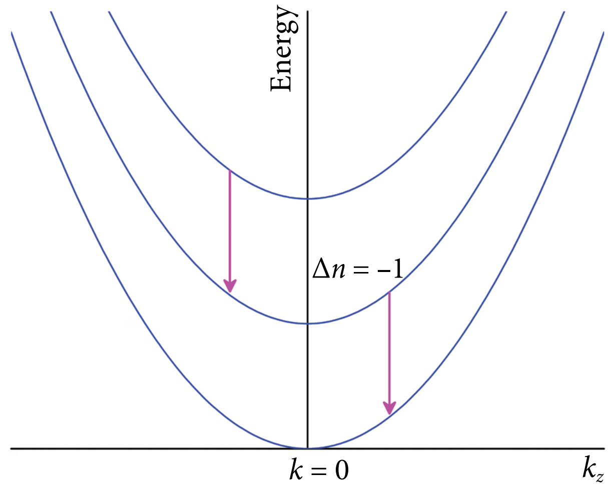

Fig. 5. Landau level dispersion with emission transitions indicated by arrows.

The first reports on Landau level emission led to the search for Landau level emission in other semiconductor structures, extensive research of the band structure of semiconductors, and development of methods for modelling the hot-carrier distribution.

In bulk n-type semiconductors, short electron scattering time in the upper Landau levels prevents population inversion between Landau levels. A different situation is found in p-type semiconductors. In crossed electric and magnetic fields, the interplay between the carrier streaming and the strong optical phonon scattering can result in an inverted hot-carrier distribution [42]. The first realization of a Landau level laser for light holes in p-Ge was reported in 1983 [43].

The Landau level laser demonstrates a wide continuous magnetic tunability. The laser line with simple mirror resonators spans the region between 1 and 3 THz with power levels of 10 to 50 mW. The limiting intrinsic gain linewidth of the laser is estimated to be 0.1 cm^{-1}, which is related with the light hole Landau level lifetime of ~300 ps [44]. The lasers are not convenient for direct implementations due to operating temperatures below 40 K, operation in the pulsed mode in the microsecond range, and the necessity of magnetic fields of within 1–5 T. Another issue is the Auger scattering of Landau-quantized electrons, an intrinsic non-radiative recombination channel that usually gains over cyclotron emission. In gapless HgCdTe, the undesirable Auger scattering is strongly suppressed [45] making therefore HgCdTe one of promising materials of choice for future Landau level lasers.

Despite the Landau level concept has not yet progressed to the design of reliable and practical light sources, Landau levels represent fundamental quantum phenomena in modern electronic and solid-state physics, inspiring various research such as topological insulators, photonic crystals, and optoelectronic materials [46].

2.4. Josephson junction-related effects in THz range

Physics behind the superconducting sources of high-frequency radiation relies on the Josephson effect [47] – manifestation of the macroscopic quantum coherence in the superconducting state. Under application of dc voltage over the Josephson junction, consisting of two weakly coupled superconducting electrodes, a superconducting alternating current will flow through the structure at the Josephson frequency [48]. Hence, the Josephson junction is a natural converter of dc voltage into high-frequency current, where, e.g. 1 mV corresponds to a frequency of 0.4836 THz. The frequency of radiation is proportional to the applied voltage thus making the effect suitable for the design of electrically tunable frequency sources. For instance, niobium with a superconducting transition temperature of $T_c = 9.2$ K has a gap energy of 1.5 meV, which corresponds to a maximum frequency of 725 GHz [49]. However, for practical needs, such operational temperature is not suitable, therefore, high-T_c can be a favourable option for developments of compact solid state THz devices. As a promising breakthrough can be assumed the employment of intrinsic Josephson junctions in the layered high-temperature superconductor $Bi_2Sr_2CaCu_2O_8$ – it was shown that in the structure containing a large number of junctions, a macroscopic coherent state can be generated, which can oscillate at frequencies up to 0.85 THz with power in the range of 0.5 μW around 50 K [50].

Recent investigation stimulated further progress in the development of the high critical temperature superconductor intrinsic Josephson junction, with a special attention to the temperature inhomogeneity management with synchronization, and the emission intensity allowed one to reach the generated frequency up to 2.4 THz [51]. As a promising and encouraging result, one can assume a very recent development of source-on-a-chip THz emitter based on a layered high-temperature superconductor, engineered with an elliptical microcavity and capable of sustained coherent emission up to 60 K, delivering stable radiation in the 0.7–0.8 THz range with on-chip electrical tunability from 100 GHz to 1 THz [52].

3. What was left beyond the predictions of the year 1985?

The scientific prediction by Acad. Juras Požela relied focusing mainly on novel physical principles that can be employed for bridging the THz gap via solid-state based emission and sensing devices. Therefore, already known principles, for instance, frequency multiplication or thermal emission, were slightly away from a special scientific attention. However, a tremendous breakthrough in device processing, advances in materials design and semiconductor nanotechnology have enabled the appearance of a new generation of semiconductor devices. We further briefly refer to recent achievements and prospects to cover the entire range of THz frequencies via approaches that have appeared recently.

3.1. Frequency multipliers for THz range

THz range frequency multipliers based on whisker diodes emerged in 1960's [53] and offered an excellent performance at the time in terms of switching speed due to the minimum shunt resistance of Schottky contact. Since the 1990s, planar Schottky diode technology has replaced fragile whisker-contacted diodes offering as an advantage their superior mechanical reliability, reproducibility, and monolithic integration capabilities but at the cost of increased shunt resistivity, which limits the speed of the device [54, 55]. Planar devices, commonly fabricated using GaAs, allow the active area of the diode to be reduced to a fraction of a square micron, thereby limiting the intrinsic junction capacitance to a fraction of a femtofarad. The physical characteristic of the Schottky barrier diode, specifically operating as a varactor, defines the performance of THz frequency multipliers. Key challenges at THz frequencies involve mitigating parasitic capacitances and series resistances, which can be done by introduction of an air-bridge anode contact. This is especially important at higher frequencies, where circuit sizes become smaller and more loss is introduced, reducing the efficiency and thus the output power of the multiplier significantly. For example, in Ref. [56], for the hybrid integration devices, the 4.7% efficiency was reported at 332.8 GHz. Meanwhile, advanced techniques such as the monolithic membrane diode (MOMED) [57] process enable the removal of the underlying GaAs substrate, leaving a thin monolithic membrane (a few micrometres thick), on which the multiple anodes, couplers, and bias leads can be integrated allowing for the operation at frequencies from 2.48 to 2.75 THz with the 1% efficiency of the final tripler stage [58].

To elevate the output power, different techniques both at the device level (multi-anode structures) and the circuit level (integrating multiple chips via Y-junctions or hybrid couplers) to overcome heating and breakdown limitations are employed. For instance, in a dual-chip tripler it allows one to achieve 26 mW at 318 GHz with 11% efficiency [59]. Further progress enabled sources displaying more than 1 mW of power across the 840–900 GHz band at room temperature [60]; theoretically, it is underlined to achieve 140 μW at 1.6 THz and 30 μW at 2.4 THz from optimized cascaded multiplier chains. State-of-the-art frequency multipliers fabricated by *Virginia Diodes* can reach the frequency of 2.2 THz.

To handle higher powers, GaN is preferable for the investigation and implementation for initial multiplier stages due to its wide bandgap, which provides a higher reverse breakdown voltage and a better thermal stability. Although GaN traditionally suffers from a lower electron mobility leading to a high series resistance, the unpreceded output power at 200 mW in the 177–183 GHz frequency band has been reported [61]. Recently, quasi-vertical GaN Schottky-barrier diodes on SiC substrates have achieved a breakdown voltage of 27.5 V [62] demonstrating desirable power-handling characteristics though efforts are still needed to reduce the associated high series resistance.

3.2. Thermal emitters for THz range

The manipulation of thermal radiation, characterized by broadband, incoherent and isotropic properties, has undergone a revolutionary transformation driven by advancements in nanophotonics and metamaterials [63, 64]. Thermal emission is governed by the fundamental principle of Kirchhoff's law of thermal radiation, stating that the spectral emissivity of an object is equal to its absorptivity for a given frequency, direction and polarization. The primary challenge throughout the history of thermal emitters has been to engineer a material to maximize absorptivity only at target wavelength while suppressing it elsewhere. The initial efforts focused on the near-infrared (NIR) and mid-infrared (MIR) regions, primarily for applications such as thermophotovoltaics and NDIR sensing [65, 66]. Early devices utilized wavelength-scale metallic nanostructures, including 2D microcavity arrays and photonic crystals [67, 68].

In the THz range, there is a need to isolate emission at THz frequencies from the broader thermal spectrum – as a rule, it is isotropic, and this limits the applicability of conventional thermal sources in many THz spectroscopic or imaging techniques. In 2012, Acad. Juras Požela and his team demonstrated an approach employing selective semiconductor reflectors operating within the 5–22 THz range [69]. Diffraction gratings and matrix filters deposited on the crystal surface can also serve as tools to extract coherent and directed THz emission from the otherwise broadband thermal radiation of heated surface [70–72].

In 2014, Acad. Juras Požela's group proposed to explore an alternative approach for controlling the emission, reflection, and transmission of thermal radiation from a heated semiconductor into free space [73]. This method exploits intrinsic features of the dielectric function at the semiconductor–free-space interface, enabling the selective manipulation of THz radiation without the need for external filtering structures, however, at a cost of a narrow spectrum range of operating frequencies [74]. Other platforms specifically engineered for THz emission can include, e.g. metamaterial-based selective emitters that can cover the range of 4 to 8 THz interval with near-unity peak emissivity [75] and/or semiconductors-based emitters, utilizing, for example, a n-GaAs/GaAs/TiAu stack [76]. The latter illustration is shown in Fig. 6(a). Here, the insulating GaAs layer acts as a cavity between the cut-wire pairs comprised of the n-GaAs substrate and the metallic metasurface. These emitters exhibit narrow emission peaks with the main harmonics below 1.5 THz with quality factors Q between 3.3 and 5.2 at temperatures of 390°C

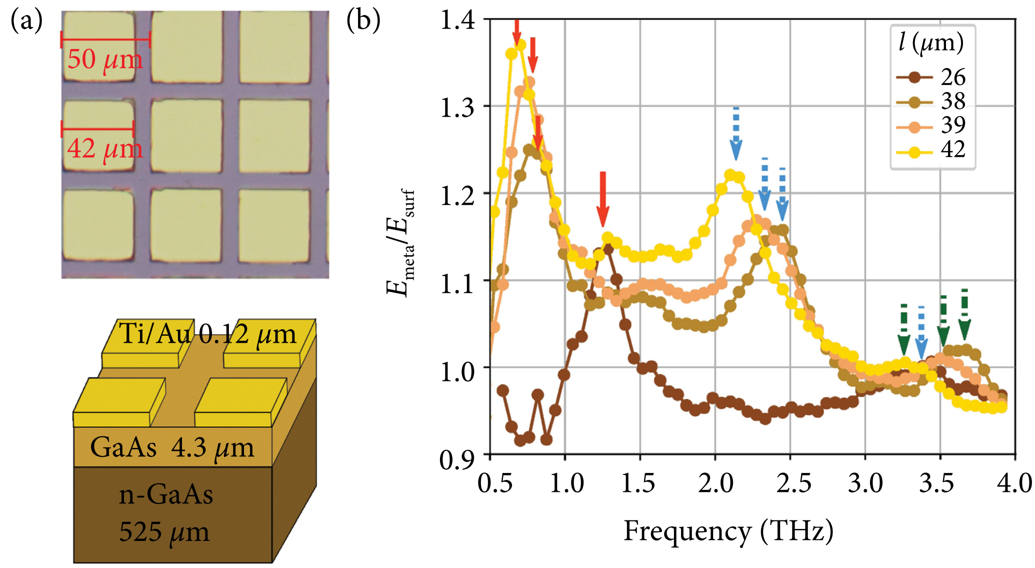

Fig. 6. The inner structure and the top metasurface view of the thermal emitter. (b) Emission spectra of thermal emitters for different square metaatom sizes. Solid arrows denote the main harmonics, dashed ones show the 3rd harmonics and dash-dotted arrows show the 5th harmonics peaks.

(Fig. 6(b)). The higher harmonics in such a system could reach frequencies up to 3.5 THz. The cut-wire pairs can be sensitive to light polarization, see Ref. [77], where the resonant thermal emission of rectangular metaatoms was shown at different frequencies depending on polarization. Furthermore, the completely GaAs-based THz thermal emission structures where n-GaAs was used as the material for metasurface instead of Ti/Au were presented in Ref. [78]. The operational frequencies of such emitters were shown to be the same as in the case of metallic metasurface, however, the quality factor of emission resonances was increased up to 30%.

3.3. Electrically pumped THz emitters relying on GaN structures

One can resolve three strategies for the development of electrically pumped terahertz (THz) emitters based on III-nitride heterostructures [79]. The first strategy involves the investigation of 2D plasmons in grating-gated AlGaN/GaN heterostructures at temperatures above that of liquid nitrogen; the second strategy is based on THz electroluminescence arising from shallow impurities, such as oxygen and silicon, within standard AlGaN/GaN high-electron-mobility transistor (HEMT) structures, while the third one is dedicated to the excitation of surface plasmon–phonon polaritons (SPPhPs) in n-GaN with gated gratings for the generation of electrically pumped THz sources under thermal and electrical stimulation producing directive and coherent radiation.

The first strategy is that III–V group nitride materials have long attracted a significant attention as promising candidates for high-frequency, high-power electronic devices capable of operating at elevated temperatures [80]. The generation of THz frequencies by direct current flow in field-effect transistor channels relies on the excitation of plasma waves [2]. While theoretical estimates suggested that 2DEG plasmonic devices could emit radiation with powers up to 2 mW, experimental observations in AlGaN/GaN heterostructures revealed only a fraction of this predicted output [81, 82]. The peak emission power and energy conversion efficiency at the expected plasmon-resonance frequency were initially reported as 940 nW and 42×10^{-9}, respectively [81]. Subsequent experiments confirmed similar emission power and wall-plug efficiency values for electrically excited 2D plasmons in AlGaN/GaN heterostructures, highlighting the advantage of operating at lower excitation powers to maintain a relatively high conversion efficiency [82].

Ability of GaN-based heterostructures to demonstrate a strong plasmonic behaviour at relatively high temperatures, above the liquid nitrogen one [83] which is in sharp contrast to traditional GaAs-based systems, makes them not only promising candidates for future THz components and devices [84, 85] but also unveils attractive and elegant physics [86].

The second strategy is based on THz electroluminescence arising from shallow impurities, such as oxygen and silicon, within standard AlGaN/GaN high-electron-mobility transistor (HEMT) structures. That topic attracted particular attention [87] as the fabrication of impurity-based emitters and is technologically less demanding compared to multi-quantum-well quantum cascade laser structures despite of their deeper cryogenic cooling. Notably, electroluminescence from shallow donors in GaN epilayers has been demonstrated at 80 K [88], and more recently, sufficient emission power has been achieved from shallow impurities in standard AlGaN/GaN HEMT structures at 110 K [89]. At higher temperatures, thermal quenching of THz electroluminescence occurs, emphasizing the advantage of HEMT structures grown on silicon carbide rather than sapphire substrates for achieving a stronger THz emission from shallow impurities [90].

The third strategy considers the excitation of surface plasmon–phonon polaritons (SPPhPs) in n-GaN gratings for the generation of electrically pumped THz sources under thermal and electrical stimulation, producing directive and coherent radiation. Remarkably, the emission frequency in these approaches can be controlled either via the gate voltage (in the case of 2D plasmons) or through structural design parameters (for SPPhPs).

Enhanced light–matter interactions via polaritonic modes have been observed in various 2D [91]. Due to a comparatively low damping factor of phonons relative to plasmons, the excitation of surface phonon polaritons (SPhPs) exhibits quality factors an order of magnitude higher than those achievable with plasmonic devices [92]. The excitation of hybrid SPPhP modes was also proposed in n-GaN gratings [93]. The thermally or electrically stimulated radiative decay of SPPhP modes in surface-relief gratings presents a promising mechanism for developing narrowband, coherent emitters in the THz and infrared spectral ranges.

Collectively, these developments have motivated the scientific community to exploit plasma and polariton waves in semiconductors for the realization of scalable, tunable THz emitters driven by external electric fields [79].

3.4. Semiconductor quantum structures for THz frequencies: quantum cascade lasers, resonant tunnelling diodes and semiconductor superlattices

Quantum cascade lasers (QCLs) can be assumed as a remarkable achievement of materials engineering using semiconductor quantum structures to allow the generation of THz radiation in electrically pumped heterostructures [4]. In contrast to conventional semiconductor lasers, where electron–hole recombination plays an essential role in light emission, the QCLs employ intrasubband electron transitions in a cascade scheme. As energy THz quanta are extremely small (e.g. below 10 meV for frequencies lower than 2.4 THz), it makes technically challenging the generation and manipulation of the THz light within the structure. Due to these issues, the lowest emission frequency in THz QCLs without the application of magnetic field is 1.2 to 1.32 THz with the pulsed mode operation up to 69 K and power of 0.12 mW at 10 K [94].

From their invention, THz quantum cascade lasers experienced tremendous developments [95]; however, room temperature operation has not yet been achieved – the maximum operating temperature of 250 K was achieved for THz QCLs operating at ~4 THz with powers in the μW range [96], and with further improvements up to 261 K [97]. The highest emission frequency reached in GaAs-based materials systems is 5.71 THz – it is the highest reported frequency for a THz QCL in the cw mode [98]. It is indicated that waveguide losses associated with the doped contact layers and metallization are a critical limitation to the device performance above 5 THz.

Resonant tunnelling diodes (RTDs), in contrast to THz QCLs, do not suffer from temperature limitations – their operation relies on resonant-tunnelling effects in semiconductor quantum structures, for instance, InGaAs quantum well and AlAs double barriers as a main part of the device epitaxially grown on a semi-insulating (SI) InP substrate [99]. These room temperatures operating compact devices allow one to reach oscillation up to 1.98 THz [100] and output power of 0.7 mW at 1 THz using a large-scale RTDs array [101]. Oscillators integrated with varactor diodes and their arrays exhibit a wide electrical tuning of 420–970 GHz, therefore, enabling the application of these compact solid-state devices for spectroscopical measurements [102].

Semiconductor quantum superlattices are artificially engineered structures made of alternating semiconductor materials, aiming to create energy minibands through the control of composition, quantum well and barrier thicknesses [103, 104]. Presence of the region of negative differential conductivity allows one to employ these structures for high frequency generation and amplification. For instance, a biased superlattice in a negative resistance state can be a gain medium for THz radiation and be used for frequency multipliers in subTHz, up to 300 GHz range at room temperature [105]. Superlattices can also be employed as room temperature amplifiers by tuning the structure into the so-called dispersive Bloch gain regime [106]. It was shown theoretically that Bloch oscillations can serve as a compact electrically-driven source of THz radiation [107, 108].

Very recently, dissipative parametric gain in a GaAs/AlGaAs superlattice at room temperature has been demonstrated [109] confirming the earlier presented theoretical prediction [110]. It was shown that it enforces the excitation of slow electrostatic waves in the superlattice that provide a significant enhancement of the gain coefficient reaching the value of the order of 10^4 cm^{-1} [109]. Moreover, it was revealed that the simultaneous application of dc and ac electric fields can induce a coexistence or interplay between coherent parametric gain and incoherent Bloch gain processes [111, 112]. The presence of multiple gain mechanisms provides a more comprehensive explanation for experimentally observed behaviours and deepens the understanding of the underlying dynamics in superlattice structures. As the frequency cut-off is related to the Bloch one, which in these wide miniband superlattices reaches 800 GHz, these studies pave the way for the development of a miniature solid-state parametric generator for subTHz frequencies.

4. Conclusions

The summary of the scientific predictions of Acad. Juras Požela of 1985 and current achievements in

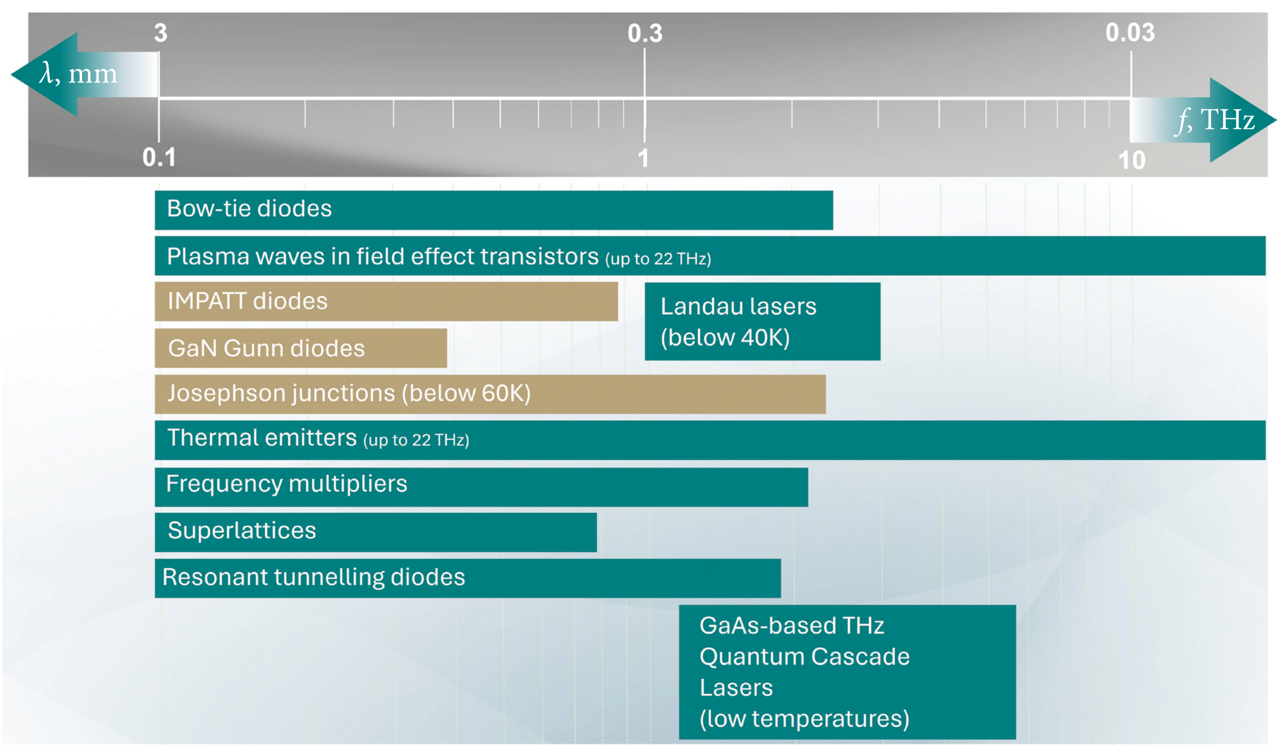

Fig. 7. Graphical summary of the devices for the THz range to date.

solid-state based THz sources and detectors are presented in Fig. 7 given below.

One can see that there is a variety of the devices bridging nearly all the THz frequency range. However, solid state-based and compact electrically driven devices, in particular, room-temperature THz emission sources meet big challenges in increasing the emission power. THz quantum cascade lasers still do not operate at room temperature, while power of resonant tunnelling diodes needs to be increased or effective amplifiers for THz need to be developed. It is important both for rapidly evolving 6G wireless communication systems as well as for further development of compact THz imaging. Integration of THz optics with emitters and detectors, room temperature broadband THz sensors, THz integrated circuits… All these ambitious topics open a plenty of room for further scientific investigations and technological developments.

Acknowledgements

When we talk about giants of science, their large-scale activities and essential impact on scientific community and society in general, as a rule, it is often commonly said that they were men before their time. When we look back and consider importance of overall activities of Acad. Juras Požela, visionary and transformative physicists, who tremendously influenced many fields of semiconductor physics and, in general, the evolution of science in Lithuania, one can claim that in crucial scientific respects he was very much a man of his time; even more, he was a man who, due to his sensitive scientific intuition, surpassed his time. His versatility and gifted feeling in view on scientific trends, deeply sensitive intuition and great predictions allowed him to initiate novel research, to inspire semiconductor scientists for competitive research on the world-class level even using relatively modest experimental facilities available in the laboratories of those times. His heritage includes more than 400 scientific publications, more than 100 inventions, and 9 monographs. He displayed an ability to see and activate the whole scientific and innovation landscape starting from semiconductor research up to their direct implementation in real devices. Currently, we are calling it 'the entire value chain'. He initiated the establishment of the pilot plant Helikonas, which produced semiconductor devices and equipment developed in former Semiconductor Physics Institute's laboratories. In 1981, the scientific production complex Elektronika under supervision of Acad. Juras Požela was founded to coordinate the development and production of semiconductor devices as well as novel radio-electronic equipment in Lithuania.

Academician was a genial and kind person with a subtle feeling of humour, he was attentive to the people around him. His role went far beyond that of a scholar and educator, founder of internationally recognized scientific school.

We had a privilege to see those inspiring activities in reality and from very close quarters; we have benefited, and can still learn a lot, from his encouraging example.

References

[1] J. Požela and V. Jucienė, *Physics of High-speed Transistors* (Vilnius, Mokslas, 1985), https://doi.org/10.1007/978-1-4899-1242-8 [in Russian].

[2] M. Dyakonov and M.S. Shur, Shallow water analogy for a ballistic field effect transitor: New mechanism of plasma wave generation by dc current, Phys. Rev. Lett. **71**, 2465–2468 (1993), https://doi.org/10.1103/PhysRevLett.71.2465

[3] J. Faist, F. Cappaso, D.L. Sivco, C. Sirtori, A.L. Hutchinson, and A.Y. Cho, Quantum cascade laser, Science **264**, 553–556 (1994), https://doi.org/10.1126/science.264.5158.553

[4] R. Köhler, A. Tredicucci, F. Beltram, H.E. Beere, E.H. Linfeld, A.G. Davies, D.A. Ritchie, R.C. Iotti, and F. Rossi, Terahertz semiconductor heterostructure laser, Nature (London) **417**, 156–159 (2002), https://doi.org/10.1038/417156a

[5] A. Acharyya and J.P. Banerjee, Prospects of IMPATT devices based on wide bandgap semiconductors as potential terahertz source, Appl. Nanosci. **4**, 1 (2014), https://doi.org/10.1007/s13204-012-0172-y

[6] H. Eisele and G.I. Haddad, Two-terminal millimeter-wave sources, in: *Proceedings of the Topical Symposium on Millimeter Waves* (IEEE, 1997), https://doi.org/10.1109/TSMW.1997.702438

[7] R.V. Mickevičius, J. Pozela, and A. Reklaitis, Theoretical investigation of impact-ionized plasma instability in GaAs, in: *Proceedings of the 8th International Conference on Infrared*

and Millimeter Waves (IEEE, 1983), https://doi.org/10.1109/IRMM.1983.9126429

[8] A. Namajūnas, A. Tamaševičius, G. Mykolaitis, S. Bumelienė and J. Požela, Microplasma noise stimulated by microwave electric field, Acta Phys. Pol. A **107**, 369 (2005).

[9] K.J. Chen, O. Häberlen, A. Lidow, C.I. Tsai, T. Ueda, and Y. Uemoto, GaN-on-Si power technology: devices and applications, IEEE Trans. Electon. Dev. **64**, 779 (2017), https://doi.org/10.1109/TED.2017.2657579

[10] Y. Dai, Y. Li, L. Gao, J. Zuo, B. Zhang, C. Chen, Z. Wang, and W. Zhao, AlGaN/GaN bilateral IMPATT device by two-dimensional electron gas for terahertz application, J. Appl. Phys. 135, 154502 (2024), https://doi.org/10.1063/5.0196188

[11] E. Alekseev and D. Pavlidis, Large-signal microwave performance of GaN-based NDR diode oscillators fundamental frequency in the range of 0.3–0.4 THz with reliable characteristics, Solid State Electron. **44**, 941–947 (2000), https://doi.org/10.1016/S0038-1101(00)00011-3

[12] A. Iñiguez-de-la-Torre, I. Iñiguez-de-la-Torre, J. Mateos, T. Gonzalez, P. Sangare, M. Faucher, B. Grimbert, V. Brandli, G. Ducournau, and C. Gaquiere, Searching for THz Gunn oscillations in GaN planar nanodiodes, J. Appl. Phys. **111**, 113705 (2012), https://doi.org/10.1063/1.4724350

[13] A.S. Hajo, O. Yilmazoglu, A. Dadgar, F. Küppers, and T. Kusserow, Reliable GaN-based THz Gunn diodes with side-contact and field-plate technologies, IEEE Access **8**, 84116 (2020), https://doi.org/10.1109/ACCESS.2020.2991309

[14] S. Ašmontas, Study of electron heating by nonuniform electric fields in n-Si, Phys. Status Solidi A **31**, 409–415 (1975), https://doi.org/10.1002/pssa.2210310208

[15] S. Ašmontas, J. Požela, and K. Repšas, Investigation of I–V characteristics of Ge and Si asymmetrically necked samples, Liet. Fiz. Rinkinys **15**, 249–258 (1975).

[16] A. Sužiedėlis, S. Ašmontas, J. Gradauskas, G. Valušis, and H.G. Roskos, Giga- and terahertz frequency band detector based on an asymmetrically-necked n–n+-GaAs planar structure, J. Appl. Phys. **93**, 3034–3038, (2003), https://doi.org/10.1063/1.1536024

[17] D. Seliuta, I. Kašalynas, V. Tamošiunas, S. Balakauskas, Z. Martūnas, S. Ašmontas, G. Valušis, A. Lisauskas, H.G. Roskos, and K. Köhler, Silicon lens-coupled bow-tie InGaAs-based broadband terahertz sensor operating at room temperature, Electron. Lett. **42**, 825–827 (2006), https://doi.org/10.1049/el:20061224

[18] I. Kašalynas, R. Venckevičius, D. Seliuta, I. Grigelionis, and G. Valušis, InGaAs-based bow-tie diode for spectroscopic terahertz imaging, J. Appl. Phys. **110**, 114505 (2011), https://doi.org/10.1063/1.3658017

[19] I. Kašalynas, R. Venckevičius, and G. Valušis, Continuous wave spectroscopic terahertz imaging with InGaAs-based bow-tie diodes at room temperature, IEEE Sensors, **13**, 50–54 (2013).

[20] S. Ašmontas, M. Anbinderis, A. Čerškus, J. Gradauskas, A. Sužiedėlis, A. Šilėnas, E. Širmulis, and V. Umansky, Gated bow-tie diode for microwave to sub-terahertz detection, Sensors **20**, 829 (2020), https://doi.org/10.3390/s20030829

[21] I. Kašalynas, D. Seliuta, R. Simniškis, V. Tamošiunas, K. Köhler, and G. Valušis, Terahertz imaging with bow-tie InGaAs-based diode with broken symmetry, Electron. Lett. **45**, 833–835 (2009), https://doi.org/10.1049/el.2009.0336

[22] L. Minkevičius, V. Tamošiunas, I. Kašalynas, D. Seliuta, G. Valušis, A. Lisauskas, S. Boppel, H.G. Roskos, and K. Köhler, Terahertz heterodyne imaging with InGaAs-based bow-tie diodes, Appl. Phys. Lett. **99**, 131101 (2011), https://doi.org/10.1063/1.3641907

[23] J. Jorudas, D. Seliuta, L. Minkevičius, V. Janonis, L. Subačius, D. Pashnev, S. Pralgauskaitė, J. Matukas, K. Ikamas, A. Lisauskas, E. Šermukšnis, A. Šimukovič, J. Liberis, V. Kovalevskij, and I. Kašalynas, Terahertz bow-tie diode based on asymmetrically shaped AlGaN/GaN heterostructures, Lith. J. Phys. **63**, 191–201 (2023), https://doi.org/10.3952/physics.2023.63.4.1

[24] L. Minkevičius, V. Tamošiūnas, K. Madeikis, B. Voisiat, I. Kašalynas, and G. Valušis, On-chip integration of laser-ablated zone plates for detection enhancement of InGaAs bow-tie terahertz

detectors, Electron. Lett. **50**, 1367–1369 (2014), https://doi.org/10.1049/el.2014.1893

[25] R. Ivaškevičiūtė-Povilauskienė, P. Kizevičius, E. Nacius, D. Jokubauskis, K. Ikamas, A. Lisauskas, N. Alexeeva, I. Matulaitienė, V. Jukna, S. Orlov, L. Minkevičius and G. Valušis, Terahertz structured light: nonparaxial Airy imaging using silicon diffractive optics, Light Sci. Appl. **11**, 326, 13 (2022), https://doi.org/10.1038/s41377-022-01007-z

[26] S. Orlov, K. Stanaitis, P. Kizevičius, P. Šlevas, E. Nacius, L. Minkevičius, and G. Valušis, Single-pixel terahertz imaging with enhanced edge detection using angular momentum of structured light, APL Photon. **10**, 050805 (2025), https://doi.org/10.1063/5.0255550

[27] S. Orlov, R. Ivaškevičiūtė-Povilauskienė, K. Mundrys, P. Kizevičius, E. Nacius, D. Jokubauskis, K. Ikamas, A. Lisauskas, L. Minkevičius, and G. Valušis, Light engineering and silicon diffractive optics assisted nonparaxial terahertz imaging, Laser Photonics Rev. **18**, 2301197 (2024), https://doi.org/10.1002/lpor.202301197

[28] T. Ando, A.B. Fowler, and F. Stern, Rev. Electronic properties of two-dimensional systems, Mod. Phys. **54**, 437 (1982), https://doi.org/10.1103/RevModPhys.54.437

[29] J. Požela and B. Pamplin, *Plasma and Current Instabilities in Semiconductors*, International Series in the Science of the Solid State (Elsevier Science, Burlington, 1981), https://doi.org/10.1016/C2013-0-05933-6

[30] S.J. Allen Jr., D.C. Tsui, and R.A. Logan, Observation of the two-dimensional plasmon in silicon inversion layers, Phys. Rev. Lett. **38**, 980 (1977), https://doi.org/10.1103/PhysRevLett.38.980

[31] G. Valušis, A. Lisauskas, H. Yuan, W. Knap, and H.G. Roskos, Roadmap of terahertz imaging 2021, Sensors **21**, 4092 (2021), https://doi.org/10.3390/s21124092

[32] M. Dyakonov and M.S. Shur, Detection, mixing and frequency multiplication of terahertz radiation by two-dimentional electronic fluid, IEEE Trans. Electron Devices **43**, 380–387 (1996), https://doi.org/10.1109/16.485650

[33] A. Lisauskas, U. Pfeiffer, E. Öjefors, P.H. Bolívar, D. Glaab, and H.G. Roskos, Rational design of high-responsivity detectors of terahertz radiation based on distributed self-mixing in silicon field-effect transistors, J. Appl. Phys. **105**, 114511 (2009), https://doi.org/10.1063/1.3140611

[34] E. Javadi, D.B. But, K. Ikamas, J. Zdanevičius, W. Knap, and A. Lisauskas, Sensitivity of field-effect transistor-based terahertz detectors, Sensors **21**, 2909 (2021), https://doi.org/10.3390/s21092909

[35] R. Al Hadi, H. Sherry, J. Grzyb, Y. Zhao, W. Forster, H.M. Keller, A. Cathelin, A. Kaiser, and U.R. Pfeiffer, A 1 k-pixel video camera for 0.7–1.1 THz imaging applications in 65-nm CMOS, IEEE J. Solid-State Circuits **47**, 2999–3012 (2012), https://doi.org/10.1109/JSSC.2012.2217851

[36] J. Holstein, N.K. North, M.D. Horbury, S. Kondawar, I. Kundu, M. Salih, A. Krysl, L. Li, E.H. Linfield, J.R. Freeman, A. Valavanis, A. Lisauskas, and H.G. Roskos, 8 × 8 patch-antenna-coupled TeraFET detector array for terahertz quantum-cascade-laser applications, IEEE Trans. THz Sci. Technol. **99**, 1–11 (2024), https://doi.org/10.1109/TTHZ.2024.3438429

[37] A. Soltani, F. Kuschewski, M. Bonmann, A. Generalov, A. Vorobiev, F. Ludwig, M.M. Wiecha, D. Čibiraitė, F. Walla, S. Winnerl, S.C. Kehr, L.M. Eng, J. Stake, and H.G. Roskos, Direct nanoscopic observation of plasma waves in the channel of a graphene field-effect transistor, Light Sci. Appl. **9**, 97 (2020), https://doi.org/10.1038/s41377-020-0321-0

[38] S. Regensburger, M. Mittendorff, S. Winnerl, H. Lu, A.C. Gossard, and S. Preu, Broadband THz detection from 0.1 to 22 THz with large area field-effect transistors, Opt. Express **16**, 20733–20741 (2015), https://doi.org/10.1364/oe.23.020732

[39] J. Schneider, Stimulated emission of radiation by relativistic electrons in a magnetic field, Phys. Rev. Lett. **2**, 504 (1959), https://doi.org/10.1103/PhysRevLett.2.504

[40] P.A. Wolff, Proposal for a cyclotron resonance maser in InSb, Physics (N.Y.) **1**, 147 (1964), https://doi.org/10.1103/PhysicsPhysiqueFizika.1.147

[41] E. Gornik, Recombination radiation from impact-ionized shallow donors in n-type InSb, Phys. Rev. Lett. **29**, 595 (1972), https://doi.org/10.1103/PhysRevLett.29.595

[42] S. Komiyama, T. Kurosawa, and T. Masumi, Streaming motion of carriers in crossed electric and magnetic fields, in: *Hot-Electron Transport in Semiconductors*, *Topics in Applied Physics*, Vol. 58, ed. L. Reggiani (Springer-Verlag,1985) pp. 177–199.

[43] Yu. Ivanov and Yu. Vasiljev, Stimulated Landau level emission in p-Ge, Sov. Tech. Lett. **9**, 264 (1983).

[44] E. Gornik and G. Strasser, Landau level laser, Nat. Photon. **15**, 875 (2021), https://doi.org/10.1038/s41566-021-00879-8

[45] D.B. But, M. Mittendorff, C. Consejo, F. Teppe, N.N. Mikhailov, S.A. Dvoretskii, C. Faugeras, S. Winnerl, M. Helm, W. Knap, M. Potemski, and M. Orlita, Suppressed Auger scattering and tunable light emission of Landau-quantized massless Kane electrons, Nat. Photonics **13**, 783–787 (2019), https://doi.org/10.1038/s41566-019-0496-1

[46] J. Pan, Z. Wang, Y. Meng, X. Fu, Y. Shen, and Q. Liu, Photonic Landau levels in an astigmatic frequency-degenerate laser, Commun. Phys. **8**, 111 (2025), https://doi.org/10.1038/s42005-025-02013-4

[47] B.D. Josephson, Possible new effects in superconducting tunneling, Phys. Lett. **1**, 251–253 (1962), https://doi.org/10.1016/0031-9163(62)91369-0

[48] U. Welp, K. Kadowaki, and R. Kleiner, Superconducting emitters of THz radiation, Nat. Photon. **7**, 702–710 (2013), https://doi.org/10.1038/nphoton.2013.216

[49] T. Van Duzer, and C.W. Turner, *Principles of Superconductive Devices and Circuits* (Elsevier, 1981), https://doi.org/10.1088/0031-9112/33/2/040

[50] L. Ozyuzer, A.E. Koshelev, C. Kurter, N. Gopalsami, Q. Li, M. Tachiki, K. Kadowaki, T. Yamamoto, H. Minami, H. Yamaguchi, T. Tachiki, K.E. Gray, W.-K. Kwok, and U. Welp, Emission of coherent THz radiation from superconductors, Science **318**, 1291–1293 (2007), https://doi.org/10.1126/science.1149802

[51] I. Kakeya and H. Wang, Terahertz-wave emission from Bi2212 intrinsic Josephson junctions: A review on recent progress, Supercond. Sci. Technol. **29**, 073001 (2016), https://doi.org/10.1088/0953-2048/29/7/073001

[52] M. Zhang, Sh. Nakagawa, Y. Enomoto, Y. Kuzumi, R. Kikuchi, Y. Yamauchi, T. Hattori, R. A. Klemm, K. Kadowaki, T. Kashiwagi, and K. Delfanazari, Tunable terahertz source on a chip with decade-long stability using layered-superconductor elliptical microcavities, Phys. Rev. Appl. **24**, 054012 (2025), https://doi.org/10.1103/pwlx-4sjf

[53] D.T. Young and J.C. Irvin, Millimeter frequency conversion using Au-n-type GaAs Schottky barrier epitaxial diodes with a novel contacting technique, Proc. IEEE **53**, 2130–2131 (1965), https://doi.org/10.1109/PROC.1965.4511

[54] W. Bishop, K. McKinney, R. Mattauch, T. Crowe, and G. Green, A novel whiskerless Schottky diode for millimeter and submillimeter wave application, in: *IEEE MTT-S International Microwave Symposium Digest*, Vol. 2 (IEEE, 1987) pp. 607–610, https://doi.org/10.1109/MWSYM.1987.1132483

[55] W. Bishop, E. Meiburg, R. Mattauch, T. Crowe, and L. Poli, A micron-thickness, planar Schottky diode chip for terahertz applications with theoretical minimum parasitic capacitance, in: I*EEE MTT-S International Microwave Symposium Digest*, Vol. 3, (IEEE, 1990) pp. 1305–1308.

[56] D.W. Porterfield, High-efficiency terahertz frequency triplers, in: *Proceedings of 2007 IEEE/MTT-S International Microwave Symposium* (IEEE, 2007) pp. 337–340, https://doi.org/10.1109/MWSYM.2007.380439

[57] P.H. Siegel, R.P. Smith, S.C. Martin, and M.C. Gaidis, THz GaAs monolithic membrane-diode mixer, IEEE Trans. Microw. Theory Techn. **47**, 596–604 (1999), https://doi.org/10.1109/22.763161

[58] J.C. Pearson, B.J. Drouin, A. Maestrini, I. Mehdi, J. Ward, R.H. Lin, S. Yu, J.J. Gill, B. Thomas, C. Lee, G. Chattopadhyay, E. Schlecht,

F.W. Maiwald, P.F. Goldsmith, and P. Siegel, Demonstration of a room temperature 2.48–2.75 THz coherent spectroscopy source, Rev. Sci. Instrum. **82**, 093105 (2011), https://doi.org/10.1063/1.3617420

[59] A. Maestrini, J.S. Ward, C. Tripon-Canseliet, J.J. Gill, C. Lee, H. Javadi, G. Chattopadhyay, and I. Mehdi, In-phase power-combined frequency triplers at 300 GHz, IEEE Microwave Wireless Compon. Lett. **18**, 218–220 (2008), https://doi.org/10.1109/LMWC.2008.916820

[60] A. Maestrini, J.S. Ward, J.J. Gill, C. Lee, B. Thomas, R.H. Lin, G. Chattopadhyay, and I. Mehdi, A frequency-multiplied source with more than 1 mW of power across the 840–900 GHz band, IEEE-MTT **58**, 1925–1932 (2010), https://doi.org/10.1109/TMTT.2010.2050171

[61] S. Liang, X. Song, L. Zhang, Y. Lv, Y. Wang, B. Wei, Y. Guo, G. Gu, B. Wang, S. Cai, and Z. Feng, A 177–183 GHz high-power GaN-based frequency doubler with over 200 mW output power, IEEE Electron Device Lett. **41**, 669–672 (2020), https://doi.org/10.1109/LED.2020.2981939

[62] G. Di Gioia, E. Frayssinet, M. Samnouni, V. Chinni, P. Mondal, J. Treuttel, X. Wallart, M. Zegaoui, G. Ducournau, Y. Roelens, Y. Cordier, and M. Zaknoune, High breakdown voltage GaN Schottky diodes for THz frequency multipliers, J. Electron. Mater. **52**, 5249–5255 (2023), https://doi.org/10.1007/s11664-023-10499-3

[63] T. Inoue, M. De Zoysa, T. Asano, and S. Noda, Realization of narrowband thermal emission with optical nanostructures, Optica **2**, 27–35 (2015), https://doi.org/10.1364/OPTICA.2.000027

[64] J. Siegel, S. Kim, M. Fortman, C. Wan, M.A. Kats, P.W. Hon, L. Sweatlock, M.S. Jang, and M.S.V.W. Brar, Electrostatic steering of thermal emission with active metasurface control of delocalized modes, Nat. Commun. **15**, 3376 (2024), https://doi.org/10.5281/zenodo.10615359

[65] J. Meléndez, A.J. de Castro, F. López, and J. Meneses, Spectrally selective gas cell for electrooptical infrared compact multigas sensor, Sens. Actuators A **47**, 417–421 (1995), https://doi.org/10.1016/0924-4247(94)00933-9

[66] J. Hodgkinson and R.P. Tatam, Optical gas sensing: A review, Meas. Sci. Technol. **24**, 012004 (2013), https://doi.org/10.1088/0957-0233/24/1/012004

[67] V. Rinnerbauer, Y.X. Yeng, W.R. Chan, J.J. Senkevich, J.D. Joannopoulos, M. Soljačić, and I. Celanovic, High-temperature stability and selective thermal emission of polycrystalline tantalum photonic crystals, Opt. Express **21**, 11482–11491 (2013), https://doi.org/10.1364/OE.21.011482

[68] S. Maruyama, T. Kashiwa, H. Yugami, and M. Esashi, Thermal radiation from two-dimensionally confined modes in microcavities, Appl. Phys. Lett. **79**, 1393–1395 (2001), https://doi.org/10.1063/1.1397759

[69] J. Požela, E. Širmulis, K. Požela, A. Šilėnas, and V. Jucienė, New type of 5–22 THz radiation sources based on semiconductor resonant reflectors, Phys. Status Solidi C, **9**, 1696–1698 (2012), https://doi.org/10.1002/pssc.201100641

[70] J.-J.J.-J. Greffet, R. Carminati, K. Joulain, J.-P.J.-P. Mulet, S. Mainguy, and Y. Chen, Coherent emission of light by thermal sources, Nature **416**, 61–64 (2002), https://doi.org/10.1038/416061a

[71] M. Geiser, G. Scalari, F. Castellano, M. Beck, and J. Faist, Room temperature terahertz polariton emitter, Appl. Phys. Lett. **101**, 141118 (2012), https://doi.org/10.1063/1.4757611

[72] V. Janonis, S. Tumėnas, P. Prystawko, J. Kacperski, and I. Kašalynas, Investigation of n-type gallium nitride grating for applications in coherent thermal sources, Appl. Phys. Lett. **116**, 112103 (2020), https://doi.org/10.1063/1.5143220

[73] K. Požela, E. Širmulis, I. Kašalynas, A. Šilėnas, J. Požela, and V. Jucienė, Selective thermal terahertz emission from GaAs and AlGaAs, Appl. Phys. Lett. **105**, 091501 (2014), https://doi.org/10.1063/1.4894539

[74] V. Janonis, R.M. Balagula, I. Grigelionis, P. Prystawko, and I. Kašalynas, Spatial coherence of hybrid surface plasmon-phonon-polaritons in shallow n-GaN surface-relief gratings, Opt. Express **29**, 13839–13851 (2021), https://doi.org/10.1364/OE.423397

[75] F. Alves, B. Kearney, D. Grbovic, and G. Karunasiri, Narrowband terahertz emitters using metamaterial films, Opt. Express **20**, 21025–21032 (2012), https://doi.org/10.1364/OE.20.021025

[76] I. Grigelionis, V. Čižas, M. Karaliūnas, V. Jakštas, K. Ikamas, A. Urbanowicz, M. Treideris, A. Bičiūnas, D. Jokubauskis, R. Butkutė, and L. Minkevičius, Narrowband thermal terahertz emission from homoepitaxial GaAs structures coupled with Ti/Au metasurface, Sensors **23**, 4600 (2023), https://doi.org/10.3390/s23104600

[77] V. Čižas, I. Grigelionis, K. Ikamas, V. Jakštas, B. Škėlaitė, D. Jokubauskis, A. Bičiūnas, A. Urbanowicz, M. Treideris, R. Butkutė, and L. Minkevičius, Polarization selective dual frequency metasurface-based resonant thermal terahertz emitters on n-GaAs/GaAs, in: *Proceedings of 2023 48th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)* (IEEE, 2023) pp. 1–2, https://doi.org/10.1109/IRMMW-THz57677.2023.10299004

[78] B. Škėlaitė, V. Cižas, K. Ikamas, V. Jakštas, D. Jokubauskis, A. Bičiūnas, A. Urbanowicz, M. Treideris, R. Butkutė, L. Minkevičius, and I. Grigelionis, Comparison of spectral properties of semiconductor structures equipped with metallic (Ti/Au) or n-type GaAs metasurfaces, in: *Proceedings of 67th International Open Readings Conference for Students of Physics and Natural Sciences* (Vilnius University Press, 2024) p. 167.

[79] V. Janonis, D. Pashnev, I. Grigelionis, V.V. Korotyeyev, R.M. Balagula, L. Minkevičius, J. Jorudas, N.V. Alexeeva, L. Subačius, G. Valušis, and I. Kašalynas, Electrically-pumped THz emitters based on plasma waves excitation in III-nitride structures, Proc. SPIE **11499**, 8 (2020), https://doi.org/10.1117/12.2569261

[80] J.J. Ibanes, M.H. Balgos, R. Jaculbia, A. Salvador, A. Somintac, E. Estacio, C.T. Que, S. Tsuzuki, K. Yamamoto, and M. Tan, Terahertz emission from GaAs-AlGaAs core-shell nanowires on Si (100) substrate: Effects of applied magnetic field and excitation wavelength, Appl. Phys. Lett. **102**, 063101 (2013), https://doi.org/10.1063/1.4791570

[81] V. Jakštas, I. Grigelionis, V. Janonis, G. Valušis, I. Kašalynas, G. Seniutinas, S. Juodkazis, P. Prystawko, and M. Leszczyński, Electrically driven terahertz radiation of 2DEG plasmons in AlGaN/GaN structures at 110 K temperature, Appl. Phys. Lett. **110**, 202101 (2017), https://doi.org/10.1063/1.4983286

[82] V.A. Shalygin, M.D. Moldavskaya, M. Ya. Vinnichenko, K.V. Maremyanin, A.A. Artemyev, V.Yu. Panevin, L.E. Vorobjev, D.A. Firsov, V.V. Korotyeyev, A.V. Sakharov, E.E. Zavarin, D.S. Arteev, W.V. Lundin, A.F. Tsatsulnikov, S. Suihkonen, and C. Kauppinen, Selective terahertz emission due to electrically excited 2D plasmons in AlGaN/GaN heterostructure, J. Appl. Phys. **126**(18), 183104 (2019), https://doi.org/10.1063/1.5118771

[83] D. Pashnev, V.V. Korotyeyev, J. Jorudas, T. Kaplas, V. Janonis, A. Urbanowicz, and I. Kašalynas, Experimental evidence of temperature dependent effective mass in AlGaN/GaN heterostructures observed via THz spectroscopy of 2D plasmons, Appl. Phys. Lett. **117**, 162101 (2020), https://doi.org/10.1063/5.0022600

[84] S. Chen, S. Duan, Y. Zou, S. Zhou, J. Wu, B. Jin, H. Zhu, W. Che, and Q. Xue, A 2DEG-based GaN-on-Si terahertz modulator with multi-mode switchable control, Adv. Opt. Mater. **12**, 2401873 (2024), https://doi.org/10.1002/adom.202401873

[85] K.R. Dzhikirba, A. Shuvaev, D. Khudaiberdiev, I.V. Kukushkin, and V.M. Muravev, Demonstration of the plasmonic THz phase shifter at room temperature, Appl. Phys. Lett. **123**, 052104 (2023), https://doi.org/10.1063/5.0160612

[86] P. Sai, V.V. Korotyeyev, M. Dub, M. Słowikowski, M. Filipiak, D.B. But, Yu. Ivonyak, M. Sakowicz, Yu.M. Lyaschuk, S.M. Kukhtaruk, G. Cywiński, and W. Knap, Electrical tuning of terahertz plasmonic crystal phases, Phys. Rev. X **13**, 041003 (2023), https://doi.org/10.1103/PhysRevX.13.041003

[87] J. Kolodzey and J.P. Gupta, Terahertz emitters based on intracenter transitions in semiconductors, Proc. SPIE **8846**, 88460E (2013), https://doi.org/10.1117/12.2024447

[88] V.A. Shalygin, L.E. Vorobjev, D.A. Firsov, V. Yu. Panevin, A.N. Sofronov, G.A. Melentyev, A.V. Antonov, V.I. Gavrilenko, A.V. Andrianov, A.O. Zakharyin, S. Suihkonen, P.T. Törma, M. Ali,

and H. Lipsanen, Impurity breakdown and terahertz luminescence in n-GaN epilayers under external electric field, J. Appl. Phys. **106**, 123523 (2009), https://doi.org/10.1063/1.3272019

[89] I. Grigelionis, V. Jakštas, V. Janonis, I. Kašalynas, P. Prystawko, P. Kruszewski, and M. Leszczynski, Terahertz electroluminescence of shallow impurities in AlGaN/GaN heterostructures at temperatures above 80 K, Phys. Status Solidi B **255**, 1700421 (2018), https://doi.org/10.1002/pssb.201700421

[90] I. Grigelionis, J. Jorudas, V. Jakštas, V. Janonis, I. Kašalynas, P. Prystawko, P. Kruszewski, and M. Leszczyński, Terahertz electroluminescence of shallow impurities in AlGaN/GaN heterostructures at 20 K and 110 K temperature, Mater. Sci. Semicond. Process **93**, 280–283 (2019), https://doi.org/10.1016/j.mssp.2019.01.005

[91] T. Low, A. Chaves, J.D. Caldwell, A. Kumar, N.X. Fang, P. Avouris, T.F. Heinz, F. Guinea, L. Martin-Moreno, and F. Koppens, Polaritons in layered two-dimensional materials, Nat. Mater. **16**, 182–194 (2017), https://doi.org/10.1038/nmat4792

[92] J.D. Caldwell, L. Lindsay, V. Giannini, I. Vurgaftman, T.L. Reinecke, S.A. Maier, and O. J. Glembocki, Low-loss, infrared and terahertz nanophotonics using surface phonon polaritons, Nanophotonics **4**, 44–68 (2015), https://doi.org/10.1515/nanoph-2014-0003

[93] V. Janonis, S. Tumėnas, P. Prystawko, J. Kacperski, and I. Kašalynas, Investigation of n-type gallium nitride grating for applications in coherent thermal sources, Appl. Phys. Lett. **116**, 112103 (2020), https://doi.org/10.1063/1.5143220

[94] C. Walther, M. Fischer, G. Scalari, R. Terazzi, Ni. Hoyler, and J. Faist, Quantum cascade lasers operating from 1.2 to 1.6 THz, Appl. Phys. Lett. **91**, 131122 (2007), https://doi.org/10.1063/1.2793177

[95] M.S. Vitiello and P. De Natale, Terahertz quantum cascade lasers as enabling quantum technology, Adv. Quantum Tech. **5**, 2100082 (2022), https://doi.org/10.1002/qute.202100082

[96] A. Khalatpour, A.K. Paulsen, C. Deimert, Z.R. Wasilewski, and Q. Hu, High-power portable terahertz laser systems, Nat. Photon. **15**, 16–20 (2021), https://doi.org/10.1038/s41566-020-00707-5

[97] A. Khalatpour, M.C. Tam, S.J. Addamane, J. Reno, Z. Wasilewski, and Q. Hu, Enhanced operating temperature in terahertz quantum cascade lasers based on direct phonon depopulation, Appl. Phys. Lett. **122**, 161101 (2023), https://doi.org/10.1063/5.0144705

[98] M. Shahili, S.J. Addamane, A.D. Kim, Ch.A. Curwen, J.H. Kawamura, and B.S. Williams, Continuous-wave GaAs/AlGaAs quantum cascade laser at 5.7 THz, Nanophotonics **13**, 1735–1743 (2024), https://doi.org/10.1515/nanoph-2023-0726

[99] M. Asada and S. Suzuki, Terahertz emitter using resonant-tunneling diode and applications, Sensors **21**, 1384 (2021), https://doi.org/10.3390/s21041384

[100] T. Maekawa, H. Kanaya, S. Suzuki, and M. Asada, Oscillation up to 1.92 THz in resonant tunneling diode by reduced conduction loss, Appl. Phys. Express **9**, 024101 (2016), https://doi.org/10.7567/APEX.9.024101

[101] 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), https://doi.org/10.1063/1.5051007

[102] S. Kitagawa, M. Mizuno, Sh. Saito, K. Ogino, S. Suzuki, and M. Asada, Frequency-tunable resonant-tunneling-diode terahertz oscillators applied to absorbance measurement, J. Appl. Phys. **56**, 058002 (2017), https://doi.org/10.7567/JJAP.56.058002

[103] L. Esaki and R. Tsu, Superlattice and negative differential conductivity in semiconductors, IBM J. Res. Dev. **14**, 61 (1970), https://doi.org/10.1147/rd.141.0061

[104] E.L. Ivchenko and G.E. Pikus, *Superlattices and Other Heterostructures: Symmetry and Optical Phenomena*, Springer Series in Solid-State Sciences, vol. 110 (Springer Berlin Heidelberg, Berlin, Heidelberg, 1997), https://doi.org/10.1007/978-3-642-60650-2

[105] K.F. Renk, B.I. Stahl, A. Rogl, T. Janzen, D.G. Pavel'ev, Yu.I. Koshurinov, V. Ustinov, and

A. Zhukov, Subterahertz superlattice parametric oscillator, Phys. Rev. Lett. **95**, 126801 (2005), https://doi.org/10.1103/PhysRevLett.95.126801

[106] P.G. Savvidis, B. Kolasa, G. Lee, and S.J. Allen, Resonant crossover of terahertz loss to the gain of a Bloch oscillating InAs/AlSb superlattice, Phys. Rev. Lett. **92**, 196802 (2004), https://doi.org/10.1103/PhysRevLett.92.196802

[107] T. Hyart, N.V. Alexeeva, J. Mattas, and K.N. Alekseev, Terahertz Bloch oscillator with a modulated bias, Phys. Rev. Lett. **102**, 140405 (2009), https://doi.org/10.1103/PhysRevLett.102.140405

[108] T. Hyart, K.N. Alekseev, and E.V. Thuneberg, Bloch gain in dc-ac-driven semiconductor superlattices in the absence of electric domains, Phys. Rev. B **77**, 165330 (2008), https://doi.org/10.1103/PhysRevB.77.165330

[109] V. Čižas, L. Subačius, N.V. Alexeeva, D. Seliuta, T. Hyart, K. Köhler, K.N. Alekseev, and G. Valušis, Observation of the dissipative parametric gain in a GaAs/AlGaAs superlattice, Phys. Rev. Lett. **128**, 236802 (2022), https://doi.org/10.48550/arXiv.2111.07715

[110] T. Hyart, A.V. Shorokhov, and K.N. Alekseev, Theory of parametric amplification in superlattices, Phys. Rev. Lett. **98**, 220404 (2007), https://doi.org/10.1103/PhysRevLett.98.220404

[111] V. Čižas, N. Alexeeva, K.N. Alekseev, and G. Valušis, Coexistence of Bloch and parametric mechanisms of high-frequency gain in doped superlattices, Nanomaterials **13**, 1993 (2023), https://doi.org/10.3390/nano13131993

[112] V. Čižas, N. Alexeeva, K. Alekseev, and G. Valušis, Sum-frequency generation and amplification processes in semiconductor superlattices, Lith. J. Phys **63**, 148 (2023), https://doi.org/10.3952/physics.2023.63.3.5

TERAHERCŲ DAŽNIŲ RUOŽO APRĖPTIS NAUDOJANT KIETOJO KŪNO PRIETAISUS

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Santrauka

Darbe trumpai apžvelgiami naujausi moksliniai pasiekimai ir pažanga, iliustruojantys neįtikėtiną akad. Juro Poželos dar 1985 m. pateiktų mokslinių prognozių tikslumą, pagrįstą jo plačia erudicija, jautria intuicija ir puikiomis įžvalgomis bei įstabiu mokslo tendencijų ir jų evoliucijos pojūčiu. Straipsnyje pateikiama struktūrizuota šiuolaikinių prietaisų apžvalga, pabrėžiant jų veikimo fiziką ir pagrindinius parametrus, taip pat aptariamos šiuolaikinės terahercų mokslo ir technologijų temos, susijusios su elektriškai kaupinamais GaN šaltiniais bei kvantinių puslaidininkinių elementų, prietaisų ir darinių, tokių kaip rezonansiniai tuneliniai diodai, kvantiniai kaskadiniai lazeriai ir kvantinių puslaidininkinių supergardelės, tyrimai. Aptariami galimi iššūkiai, susiję su aprašytų prietaisų tolesniu vystymu ir plėtra.