I. INTRODUCTION

The terahertz (THz) frequency range (often referred to as the THz gap) lies between the frequency ranges of the electronic and photonic devices. It is the next frontier of ultra-high speed electronics. First applications of the THz technology were in astronomical science [1], [2] and earth observation [3], [4]. In addition to radio astronomy and earth remote sensing, numerous applications of the THz technology include vehicle radars [5] and compact radars [6], [7], non-destructive testing [8], [9], sensing [10]–[12], chemical analysis [13], explosive detection [14], moisture content determination, coating thickness control [15], film uniformity determination [16], structural integrity testing, wireless and wireless covert communications [17]–[22], biotechnology [23]–[30], semiconductor characterization, [31], medical applications [32], [33] (including cancer detection [34], [35]), imaging [36], [37], quantum measurements [38], [39], semiconductor wafer characterization, [40], [41], VLSI testing [42]–[48] concealed weapons detection [49], and food safety control [50], [51]. The expected killer applications are in beyond 5G Wi-Fi [52], [53] (with estimated market potential of $730 billion by year 2030 [54]) and Internet of Things (approximately $20 billion market potential in 10 years [55]) using the 230-340 GHz band [19], [20], [56]. The overall THz market has remained modest but is expected to grow from approximately $220 million in 2020 to $1.3 billion in 2027 [57]. However, this growth rate might increase dramatically because of the emerging THz plasmonic technology enabling fast, inexpensive THz detectors, mixers, frequency multipliers, and sources, Focused plane Arrays (FPAs), and THz cameras [58]. This technology is compatible with modern Si VLSI technology and could take advantages of well-developed Si VLSI readout technology used for infrared FPAs and infrared cameras. Figure 1 shows the THz application areas, where the expected impact of the plasmonic THz technology will be the largest.

The paper is organized as follows. Section II considers existing and potential applications of the THz technology that are expected to be impacted by field effect transistors operating in the plasmonic regime (TeraFETs). Section III describes the physics of ballistic and quasi-ballistic transport in short channel TeraFETs and the physics of resonant and overdamped plasma waves. Section IV reviews the state-of-the performance of the THz plasmonic devices. The focus of Section V is...
Fig. 1. Subranges of the THz radiation spectrum mapped into different applications. Shaded region show the range, where plasmonics THz technology will have an impact.

Fig. 2. Chelyabinsk meteorite explosion.

Fig. 3. The image the Iras-Araki-Alcock Comet taken at 12 THz [61].

Fig. 4. Stars invisible in a dense dust cloud appear as bright stripe in the THz image [62]. Copyright: Michael Hauser (Space Telescope Science Institute), the COBE/DIRBE Science Team, and NASA.

Fig. 5. THz gas spectroscopy [63].

II. APPLICATIONS

The Chelyabinsk meteor entered Earth’s atmosphere over Russia on 15 February 15, 2013. This undetected near-Earth asteroid travelling with a speed of over 60,000 km/h exploded in an air over the Chelyabinsk region [59] (see Fig. 2). The total kinetic energy of the explosion was over 30 times larger than the energy released by the atomic bomb detonated over Hiroshima. The blast damaged 7,200 buildings and injured 1,500 people. Miraculously, nobody died.

This catastrophic event highlighted the importance of monitoring the space, and THz radiation is an important tool of space exploration. A sub-THz interferometer (IRAM) in Plateau de Bure, French Alps operates at 230 GHz. The of six 15 meters diameter antennas of the IRAM interferometer can move on rail tracks up to a maximum separation of 408 m in the East-West direction and 232 m in the North-South direction. The instrument resolution of 0.5 arcsecs is sufficient to resolving an apple at a distance of 30 km).

COBE, MIRO, ODIN, AKARI, AURA, HERSHEL, IRAS, PLANK, SMILES are examples of THz instruments or missions in space [60]. Fig. 3 shows the image of a comet (called the Iras-Araki-Alcock Comet) was discovered by Infrared Astronomical Satellite (IRAS) in its 560-mile-high, near-polar orbit above the Earth.

Fig. 4 presents another striking example of the THz applications in radio astronomy. THz detects cold matter (140 K or less), such as clouds of gas and dust in our and nearby galaxies. New stars radiate heat are clearly seen in the THz range. Stars invisible in a dense cloud of dust appear as very bright stripe in the THz image because they heat the dust that glows in far-infrared range [62].

THz gas spectroscopy is perfect for detection and identification of gases (see Fig. 5)
NASA used the THz spectroscopy for monitoring the ozone and other gases (see Fig. 6). The ozone hole in upper atmosphere lets dangerous ultraviolet radiation pass through causing skin cancer. One out of five Americans will develop skin cancer over their lifetime [64].

THz radiation penetrates fog and dust, goes through walls, allows for line-of-sight communications with or without reflections, very secure, hard to jam. The communication range varies from light years in space exploration to hundreds of meters in a city environment to the nanoscale for communications inside of a computer board or a computer chip (see Fig. 7). THz communication links are perfect for creating driverless car infrastructure in a large urban environment (see Fig. 8).

Fig. 9 illustrates the increasing demand for the bandwidth by the generations of the cellular networks that could be only addressed by sub-THz (220 GHz to 340 GHz) and THz technologies.

Fig. 10 shows the results of the explosive detection using the THz radiation. Fig. 11 shows an example of using sub-THz radiation for identifying toxic gases [67].

Fig. 12 shows the heparin detection by a TeraFET. The sensitivity is order of magnitude larger that for the ChemFET operation monitoring the changes in the transfer characteristics when the FET is exposed to heparin.

Fig. 13 present a few more applications that are expected to benefit from the plasmonic TeraFET technology.

Another recently emerging application is in cyber security and defect and reliability studies of short channel field effect transistors (see Fig. 14 and 15). This technique could complement and improve upon more traditional VLSI THz testing (see Fig. 16 and 17).

III. PHYSICS OF TERA FETS: BALLISTIC TRANSPORT AND PLASMONICS

Fig. 18 shows the power levels achieved by different THz electronic sources [44]. As seen powers generated by Si CMOS and InP-based HEMTs fit well into the overall power
Fig. 11. THz spectra of acetaldehyde (black), acetonitrile (red), ethanol (green), water (yellow), methanol (blue), ammonia (magenta), propionaldehyde, propioaldehyde (cyan), and propanenitrile propionitrile (gray) [67].

Fig. 12. Transfer characteristics with and without heparin and response of the plasma wave detector [29].

Fig. 13. The results of inspection of space shuttle insulation foam defects using a 0.2 THzGunn diode oscillator (circles indicate the found faults) [9] (a); schematics of THz skin cancer detection (b); THz communication [17] (c); sub-THz image of I7 microprocessor at $f = 288$ GHz [68] (d).

versus frequency dependence. Further improvement of their performance require design optimization based on better understanding of the device physics of ultra-short devices.

Fig. 14. Measured transfer characteristics (a), 0.2 THz responses (b) of two Si NMOS devices. $L_g = 180$ nm, 0.2 THz response images of normal (c) and defective (d) Si MOS. (After [44]).

Fig. 15. Testing MMIC under bias by measuring voltage at the package pins: MMIC photograph (a), working device (b) and damaged device (c) responses [47].

Scaling the FET feature sizes below 20 nm required a radically different FIN FET geometry. Further scaling down to 5 nm and 3 nm feature sizes required all around gate design. Such design concepts were first proposed in late 1990’s [71]–[73] (see Figures 19 and 20) but it took nearly 20 years for these designs to become mainstream Si MOS VLSI technology.

The physics of the electron transport in such devices involves ballistic and quasi-ballistic transport [74]–[92]. The electron inertia responsible for the excitations of the oscillations of the electron density (the plasma waves) plays a key role in determining the high frequency response.
The characteristic distance determining the modes of the electron transport is the mean free path \( \lambda = v_{th} \tau \) and \( \lambda = v_F \tau \) for a non-degenerate and a degenerate semiconductor, respectively. Here \( v_{th} \) and \( v_F \) are the thermal and Fermi velocity, respectively, and \( \tau \) is the momentum relaxation time. The ballistic regime takes place when the electron transit length, \( L \ll \lambda \).

Fig. 22 showing the evolution of the electron velocity for electrons injected into semiconductor for different values of the electric field illustrates this point. As seen, the electron velocity is higher than the steady-state value reached deep inside the semiconductor. This “overshoot” effect is due to the finite energy relaxation time it takes for the electrons to gain energy from the electric field and, hence, an ability to emit optical phonons. Even more interesting is the electron velocity...
dependence on distance at very small distances shown in the inset in Fig. 22. At such short distances smaller than the mean free path, the electron transport is not affected by the electron collisions with the impurities or lattice vibrations.

Fig. 23 shows typical values of the mean free path for Si and GaN. As seen, the 2DEG mean free path is much larger than the minimum feature size of modern Si CMOS even at room temperature. Therefore, understanding of the physics of the ballistic transport is crucial for the design of modern VLSI.

Fig. 24 illustrates one of the consequences of the hydrodynamic ballistic transport strongly affected by contacts, which the dependence of the apparent (measured) electron mobility on the channel length. As shown in [76], [77] the apparent “ballistic” mobility \( \mu_{bal} \) is determined by the contacts is dominant at short channel length and is proportional to the channel length \( L \): Here \( m \) is the electron effective mass, and the constant \( \alpha \) and velocity \( v \) are listed in Table I.

The AC impedance of a ballistic device is also dramatically different from that for long channel devices, since that phase relations between the electron fluxes injected form the opposite contacts start playing a dominant role [87].

Hydrodynamic model describing electrons in TeraFET channels as an electronic fluid provides an insight into the consequences of the ballistic transport.

Fig. 25 shows the characteristic response time of a semiconductor calculated in the frame of a hydrodynamic model [93].

As seen, at low mobility values (corresponding to the collision-dominated regime) the response time decreases with the electron mobility because it is determined by the electron transit time. However, for high mobilities, when the momentum relaxation time becomes larger than the transit time, the response time increases with the mobility. The reason for this increase is the oscillations of the electron density – plasma waves – that become resonant at high momentum relaxation times, i.e. at high mobility values. For very momentum relaxation times, the electron viscosity becomes a dominant attenuation mechanism and, as seen in Fig. 25, the response time saturates in the viscous electron transport regime.

The saturation level depends on the channel length and on the momentum relaxation time [94]–[96]. The detailed COMSOL simulations of the minimum response time based on the hydrodynamic model are presented in [96] for the 2DEG in InGaAs, Si, GaN, and for the two-dimensional hole gas in p-diamond.
The simulation results reported in [96] agree well with analytical theory developed in [94] yielding the characteristic inverse response time $1/\tau_r$ in the frame of the hydrodynamic model

$$\frac{1}{\tau_r} = R e \left( -\frac{1}{\tau} + \frac{\pi^2 v}{4L^2} + \sqrt{\left(1 + \frac{\pi^2 v}{4L^2}\right) - \frac{\pi^2 s^2}{L^2}} \right)$$

Here $s$ is the plasma wave velocity given by [97]

$$s = s_0 \sqrt{1 + \exp\left(-\frac{qV_o}{\eta k_B T}\right)} \ln \left[1 + \exp\left(-\frac{qV_o}{\eta k_B T}\right)\right]$$

$V_o$ is the gate voltage swing ($V_o = V_G - V_T$ with $V_G$ and $V_T$ being the gate and threshold voltage, respectively), $T$ is temperature, $s_0 = \sqrt{\eta k_B T/m}$, $\eta$ is the subthreshold ideality factor, $T$ is temperature, $k_B$ is the Boltzmann constant. The typical values of the plasma velocity are much larger than the electron drift velocity and the values of the fundamental plasma frequency correspond to the THz range (see Fig. 25). The fundamental frequency of the plasma waves for electrons in a gated MOS channel biased above threshold is $f_{p\alpha} = s/(4L)$ and $f_{ps} = s/(2L)$ for asymmetric and symmetric boundary conditions, respectively.

As seen from Fig. 26, the plasma wave velocity is much larger than the electron drift velocity in long channel devices, and a typical fundamental plasma frequency is much larger than the FET cutoff frequency, which is on the order of the inverse transit time.

Fig. 27 (from [98]) shows the dispersion relations for plasma waves. $N_{2D}$ and $N_{3D}$ are sheet and bulk carrier concentrations, $k$ is the wave vector. (From [98]).

The compact models [99] and TCAD simulations [92] are very useful in evaluating the contribution of these non-ideal effects.

## IV. THZ PLASMONIC DEVICES

The first proposal to use the plasma instability in a ballistic or quasi-ballistic TeraFET channel for generating THz radiation [100] relied on the different plasma wave reflections from the channel boundaries with the channel serving as a resonant cavity for the THz waves. This instability now (called the Dyakonov-Shur instability) predicts a relatively narrow THz emission spectrum. The Ryzhii-Satou-Shur transit time plasmonic instability [101] involving the transit time delay shifting the phase between the THz voltage and current should result in the narrow band THz emission as well. However, most papers reported on the broadband THz radiation emitted from TeraFETs [102]–[109]. A strong and narrow band emission from a single GaAs TeraFET was reported in [110]. The power level was the highest reported for the TeraFETs (63 mW at 300 and 278 mW at 77 K with 0.0486% conversion efficiency) [110]. Further studies are required to understand the mechanism responsible for this emission. Obtaining still higher power levels and higher conversion efficiencies might require collecting radiation from larger areas than just a single short channel TeraFET (see the next Section).

The rectification of the resonant or overdamped plasma oscillations could be used for the detection of the THz radiation [111], [112]. Fig. 28 (from [113]) shows the schematics of a TeraFET THz detectors with a THz signal coupled to the
Fig. 28. Plasmonic FET under THz radiation modeled with multiple segments in the channel accounting for the THz current distribution. (From [113] © IEEE2020.

Table II (from [115]) shows the estimated values of $Q_m$ and $f_p$ for Si, GaN, InGaAs, and $p$-diamond TeraFETs at 300 and 77 K. The gate swing was chosen to maximize the quality factor. As seen, resonant detection ($Q_m \gg 1$) is possible even at room temperature even though non-resonant detection is much easier to achieve.

As seen from the Table II, Si TeraFETs might become primary candidates for THz components and $p$-diamond has superb properties for THz applications, especially at the lower frequencies of the THz band [118]. Graphene TeraFETs are also emerging as competitive plasmonic THz detectors [119].

The THz radiation could couple to both sides of the TeraFET channel (see Fig. 31). The phase difference between the plasma waves excited at the source and drain depends on the plasma frequency and, hence, could be adjusted by the gate bias [113], [120], [121].

An important application of this effect is a vector detection (detecting both the amplitude and the phase of a signal) to be used for a line-of-sight detection. Measuring the gate bias, at which the response becomes equal to zero, allows using TeraFET as a THz spectrometer of interferometer. Fig. 32 shows the simulated frequency ranges, in which TeraFETs could operate as spectrometers.
fast temporal response and the compatibility of Si plasmonic TeraFETS with VLSI technology make plasmonic THz technology to be a prime candidate for closing the famous THz gap in the electromagnetic spectrum applications. THz sensing, imaging, and communications are the prime candidates for the application of the THz plasmonics with a strong commercial appeal for deploying Si based 240 GHz to 300 GHz technology for beyond 5G WI FI and IoT applications. Recently reported high narrow-band THz power emitted by a single GaAs-based TeraFET [110] is a breakthrough highlighting the emerging commercial potential of the THz plasmonic technology.

V. PLASMONIC CRYSTALS AS POTENTIAL THz RADIATION SOURCES AND DETECTORS

The attempts to increase the responsivity involve using the ratchet effect [123]–[128], grated gate structures [129]–[133], plasmonic boom [134], [135], and variable width devices [115]. We call such structures plasmonic crystals with the unit cells smaller or comparable to the mean free path but capable of capturing and processing a larger THz flux.

FET arrays and grating structures already demonstrated superior performance as THz detectors [136]–[141] in a good agreement with theoretical predictions [142]–[145]. Both the Dyakonov–Shur instability [100], [146] and “plasmonic boom” instability [134], [135] can develop in the plasmonic crystals. The plasmonic boom instability develops in a plasmonic crystal with two regions per unit cell with plasma wave velocities in these cells $s_1$ and $s_2$, such that $s_1 < v < s_2$, where $v$ is the velocity of electron flow. This could be achieved using different threshold voltages in the cells 1 and 2 or by the cells having a different width. Narrow protruding regions (plasmonic stubs) could adjust the boundary conditions between the sections and the plasmonic crystal with stubs could support RF to THz conversion (see Fig. 33).

VI. CONCLUSION

Small sizes (making it easy to fabricate arrays), high sensitivity, broad spectral range, band selectivity and tuneability

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