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Silicon Carbide Based Transit Time Devices: The New Frontier in High-power THz Electronics

Moumita Mukherjee

*Centre of Millimeter-wave Semiconductor Devices and Systems,
Institute of Radio Physics and Electronics,
University of Calcutta, India
e-mail: mm_drdo@yahoo.com*

1. Introduction

In recent years, the field of Terahertz (THz) science and technology has entered a completely new phase of unprecedented expansion that is generating ever-growing levels of broad-based international attention. Indeed, the plethora of activities that have arisen recently in both the technology and scientific arenas associated with the THz frequency domain - i.e., between 1 millimeter (300 GHz) and 100 micrometers (3 THz), suggest that the field might be attempting to undergo a dramatic transition that could lead to long-awaited payoffs in a number of application areas. The inherent advantages and potential payoffs of the THz regime for military & security as well as industry relevant applications have long stood as an important driver of interest in this science and technology area. This extremely expansive and spectrally unique portion of the EM spectrum had initial application in space-based communications, upper atmospheric sensing and potentially for short-range terrestrial communications and non-intrusive package screening. However, the very rapid growth in more recent years is arguably most closely linked to the potential payoffs of THz sensing and imaging for an array of military, security and industrial applications. These applications include the spectroscopic-based detection identification and characterization of chemical and biological agents and materials, remote and standoff early-warning for chemical-biological warfare threats, and imaging of concealed weapons and explosives, just to name a few. In addition, THz-regime finds its application possibilities in industry and private-sector areas as food-industry process control, pharmaceutical industry, biological science, medical diagnostics and security screening.

Systems for rapidly emerging applications at THz frequencies thus require reliable high-power sources. In the last few years, the development of suitable sources for this frequency regime is being extensively explored worldwide. There are broadly two technology roadmaps for THz semiconductor devices. Approaching from the lower frequency range in the THz regime, electronic devices such as, Gunn diode, Resonant Tunneling diode (RTD) and nanometer Field Effect Transistors (FET) based on plasma wave have been widely investigated for THz frequency generation. From higher portion of the THz frequency spectrum, the photonics-based device Quantum Cascade Laser (QCL) extends the emission

wavelength to Terahertz spectral range. The other approach to THz generation is through femtosecond lasers incident on materials with non-linear optical properties or on photoconductors such as InP. Parametric amplifiers are also being used for the purpose.

All the above efforts are to pursue the effective generation of THz signals. Most of the available THz sources are complex and bulky. QCL, on the other hand, has the advantage of small size, though they require low temperature operation to directly generate THz. Thus it seems that there is lack of availability of small-sized suitable THz source to serve a useful purpose. So, the development of high-power, low-cost and compact semiconductor sources in THz regime has attracted the recent attention of researchers working in this field.

Nowadays two-terminal solid-state Avalanche Transit-Time (ATT) devices are finding increasing applications in advanced RADAR, missile seekers and MM-wave communication systems. The performance of conventional Si (Silicon) and GaAs (Gallium Arsenide)-based IMPact ionization Avalanche Transit Time (IMPATT) devices are limited by power, operating temperature and especially by operating frequency. Recently, there is a global demand for THz-frequency applications and this warrants a new class of IMPATT oscillators which would outclass conventional Si and GaAs IMPATTs. Investigations on the prospects of Wide Bandgap (WBG) semiconductor materials, particularly IV-IV SiC semiconductors, for developing devices for high-frequency, high-power and high-temperature applications have been started recently.

Considering all the above facts, the author has made an attempt to study the THz-frequency characteristics of SiC-based IMPATT oscillators. In this Chapter, light will be thrown on the reliability and experimental feasibility of this new class of devices in the THz-region. Also, photo-sensitivity of these new classes of devices will be included in the chapter.

2. Importance of SiC as a base semiconductor material for IMPATT fabrication

2.1 Hexagonal SiC

SiC is recognized as a semiconductor of great importance in electronic applications because of its distinct properties, the possibility of easy growth on a native oxide, and the presence of numerous polytypes [1-4]. Silicon carbide is made up of equal parts silicon and carbon. Both are period IV elements, so they will prefer a covalent bonding such as in the left figure. Also, each carbon atom is surrounded by four silicon atoms, and vice versa. This will lead to a highly ordered configuration, a single polarized crystal. However, whereas Si or GaAs has only one crystal structure, SiC has several. The SiC family of semiconductor contains the same semiconductor material grown in many polytypes. The most commonly grown SiC materials are 4H-SiC, 6H-SiC, 3C-SiC. SiC, although of varied polytypes, generally have high carrier saturation velocity and high thermal conductivity, which make them suitable for high-temperature (above 900K), high-frequency (Terahertz region) applications [5]. Table 1 compares four semiconductors: silicon, gallium arsenide, silicon carbide and gallium nitride. Gallium Nitride is included here since in some respects it is perhaps a better material than SiC. It is also of interest to combine GaN with SiC, though the big difference is the energy bandgap. Standard semiconductors have almost three times smaller bandgaps than the wide bandgap materials SiC and GaN. However, it is probably the ten times larger critical field for breakdown which makes the biggest difference. There are no large differences in the other parameters, except the high mobility of GaAs. Cree Research Inc. [6]

was the first commercial vendor of SiC wafers which are commercially available as 4-inch wafers of 4H-SiC. It is well known that SiC wafer quality deficiencies are delaying the realization of outstandingly superior 4H-SiC high-power semiconductor devices. While efforts to date have centered on eradicating micropipes, 4H-SiC wafers and epilayers also contain elementary screw dislocations in densities on the order of thousands per cm², nearly 100 fold micropipe densities. While not nearly as detrimental to SiC device performances as micropipes, it was shown earlier that diodes containing elementary screw dislocations exhibit a 5% to 35% reduction in breakdown voltage, higher pre-breakdown reverse leakage current, softer reverse breakdown I-V knee and concentrated microplasmic breakdown current filaments when measured under DC testing conditions. At present, the micropipe densities have decreased to less than 1 cm⁻² in 4-inch wafers. 4H- and 6H- are the easiest to grow and are usually epitaxially grown on a Si substrate. Nowadays the commonly used method to grow SiC epitaxial layer is the Chemical Vapor deposition (CVD) technique. It provides good structural quality and excellent doping control. Recent advances in crystal growth and thin film epitaxy of SiC, allow the development of high-quality layers. The cubic phase, 3C-SiC, however, is difficult to grow because of lack of a suitable substrate, thus it receives less attention. However, in recent years, there has been some little interest in 3C-SiC, resulting in both experimental and theoretical works. The most difficult to grow is 2H-SiC, because of its high formation energy. The most common donors in SiC are nitrogen (N) and phosphorous (P). N substitutes on C sites in the lattice, while P on Si sites. The most common acceptors are aluminum (Al) and boron (B) which substitutes on Si sites.

Semiconductor	Si	GaAs	4H-SiC	3C-SiC	WZ-GaN	Diamond
Bandgap (E _g) (eV)	1.12	1.42	3.26	2.3	3.45	5.45
Electric Breakdown field (E _C)(10 ⁷ V.m ⁻¹)	3.0	4.0	30.0	22.0	50.0	100.0
Relative dielectric constant (ε _r)	11.9	13.1	9.7	9.72	8.9	5.5
Electron mobility (μ _n) (m ² V ⁻¹ s ⁻¹)	0.15	0.85	0.10	0.08	0.125	0.22
Hole mobility (μ _p) (m ² V ⁻¹ s ⁻¹)	0.04	0.03	0.011	0.004	0.085	0.085
Saturated drift velocity of electrons (v _{sn}) (10 ⁵ ms ⁻¹)	1.0	1.2	2.0	2.0	2.5	2.7
Thermal Conductivity (K) (Wm ⁻¹ K ⁻¹)	150.0	46.0	490.0	450.0	225.0	1200.0

Table 1. Comparison of material parameters of different semiconductors

SiC was considered to be a promising material for fabrication of IMPATT diodes for the first time in 1973 by Keys [7]. In 1998, Konstantinov et al. fabricated epitaxial p-n diodes in 4H-SiC with uniform avalanche multiplications and breakdown [8]. They have performed photo-multiplication measurements to determine electron and hole ionization rates. P-n

(i) Growth of p^{++} 4H-SiC layer: In order to assist p-type ohmic contact formation, the p^{++} 4H-SiC layer can be grown on top of the n-type film by Al^{2+} ion implantation; the doping concentration should be $N_A \geq 2 \times 10^{19} \text{ cm}^{-3}$. The post-implantation annealing may be performed at $\approx 1600^\circ \text{C}$ for 45 minutes in argon atmosphere.

(ii) Formation of low resistive p^{++} and n^{++} contacts: The power dissipation of IMPATT devices strongly depend on the contact resistance. Following step (i), the samples may be cleaned by a "piranha" solution. After rinsing in DI water, the samples may be dipped in dilute hydrofluoric (HF) acid solution for 30 seconds and dried. Immediately after the cleaning, a SiO_2 layer on the p^{++} side can be grown by Plasma Enhanced Chemical Vapor Deposition (PECVD) at 285°C . Through photolithographic process, windows can be opened inside the oxide layer. Using photolithography and lift-off techniques, contact metals (Al/Ti/Al) can then be deposited in the oxide windows by an electron beam evaporator. In order to obtain ohmic contacts the samples may be annealed for 3 minutes in a Rapid Thermal Anneal (RTA) furnace in nitrogen atmosphere at 950°C . The post-deposition annealing at high temperature is generally preferred to reduce the specific contact resistance. As mentioned in the literature, Ni is the preferred material for ohmic contact on n-type SiC (Roccaforte et al., 2006). Hence, for n^{++} -type contact, a Ni layer of 200 nm thickness may be evaporated on the back-side (n^{++} -side) of the wafer, followed by RTA treatment for 3 minutes at 950°C . The choice of the metallic composition is based on the formation of Ni_2Si alloy. As mentioned in several publications (Konishi et al, 2003), the higher the concentration of the Ni_2Si in the contacts, the lower is the specific contact resistance. Finally, a composition of Ti/Au contact overlay is deposited on the p^{++} -side by an electron beam evaporator. The specific contact resistance can be determined from transmission line measurement (TLM) data.

(iii) The oxide layer from the p^{++} -side can then be removed by Buffered Oxide Etch (BOE).

(iv) Formation of diode mesa using Reactive Ion Etching (RIE): Si-C bonds show high chemical inertness, hence, wet etching is not efficient for reaching deep trenches. The more appropriate dry plasma etching, Reactive Ion Etching (RIE), may be used in separating the diode mesa. Patterning of mesas may be carried out with photoresists: AZ 5214 (standard) and TI 35 ES (special photoresist for deep RIE Si etching) (Lazar et al., 2006). A titanium/nickel (Ti/Ni) bilayer metal can be evaporated onto the sample. The metallic bilayer may be used as RIE mask that covers areas that will form mesa diodes. The dry etching can be performed in the Plasma Therm 790 reactor (say), an RIE reactor with a plasma (composed of SF_6 and O_2 gases) source generated at 13.56 MHz operating at a maximum power of 300W. The depth and etch rate of the mask may be determined by profilometry measurements with a Tencor Alpha Step.

(v) On-Wafer DC Testing: After finishing the fabrication process, on-wafer DC testing are performed before the diodes are packaged. DC testing may serve as the initial screening step of the devices and the test results can be used for process evaluation.

(vi) SiC IMPATT Device Packaging: The packaging should provide a low thermal resistance between the SiC diode chip and wave guide mount and should be mechanically rugged and hermetically sealed. The device can be bonded to a pill-type package. In pill-type configuration, the diode is bonded to a heat sink, which is usually gold plated. A ceramic or quartz ring encloses the diode and separates the heat sink from the package cap.

4.1 Terahertz transmission and measurement

It is highly desirable that a THz transmission system should have low signal attenuation, low radiation loss, and high mode-confining property. Sommerfeld wires exhibit very low attenuation and dispersion, but suffers from large field extension into the surrounding medium. Moreover, it suffers from significant radiation loss at bendings. Metallic parallel plate waveguides, on the other hand, exhibit undistorted wave propagation of broadband sub-picosecond pulses even at bendings, but the propagating wave is confined in one transverse dimension giving rise to divergence loss. Transmission of THz signals from an IMPATT device may be possible with a dielectric coplanar wave guide, the device being an integral part of the waveguide. For THz (0.1-1 THz) signal transmission, a metallic slit waveguide, fabricated by sawing a 270 μm wide slit through a 140 mm wide and 300 μm thick silicon slabs may be used (Wachter et al., 2007). The metallic slit waveguide shows dispersion less transmission of THz signals with very low attenuation. However, the residual edge roughness from wafer sawing can cause a small degree of radiation loss. For higher frequency (3 THz) power transfer, a ribbon-like structure fabricated from ceramic alumina may be utilized (Yeh et al., 2005).

Measurements of THz power and frequency may be done with a THz VNA (Vector Network Analyzer) or, by employing Photoconductive Method. In the Terahertz regime, vector network measurements are challenging because of the reduced wavelength. Also, large phase errors resulting from temperature fluctuation can occur. In addition, flexing of the cable linking the scanning waveguide probe to the measurement equipment adds to the phase uncertainty. There are other systems for measurement and detection of THz signals for example Hot Electron Bolometer mixer- receiver and THz Time Domain Spectroscopy (THz-TDS). For detection and measurement of THz beam by photoconductive method, a THz-TDS set-up may be used (Wachter et al, 2007). The photoconductive setup can avoid the input and output coupling of free space Terahertz beams, giving rise to a compact and versatile setup. THz Time Domain Spectroscopy measurement require multiple time delay scans, which is time consuming and can result in a systemic error caused by the intensity fluctuations of the THz beam. THz-TDS has smaller spectral range than Fourier Transform Spectroscopy (FTS) system and provide lower resolution than narrowband THz spectroscopy (Ferguson and Zhang, 2002).

5. Conclusion

It may be concluded that, the results reported here, reveal the potential of hexagonal and cubic β -SiC IMPATTs as high-power THz source and the design may be used for experimental realization of SiC THz IMPATT. Based on the design, the authors have also successfully grown β -SiC p-n junction on Ge modified Si $\langle 100 \rangle$ substrate. Efforts have been made to reduce the lattice mismatch at Si/SiC interface by incorporating Ge. The preliminary results are encouraging and need further improvement to obtain 3C-SiC based IMPATTs with minimum reverse leakage current, additional results will be the subject of another paper.

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In this book, we explore an eclectic mix of articles that highlight some new potential applications of SiC and different ways to achieve specific properties. Some articles describe well-established processing methods, while others highlight phase equilibria or machining methods. A resurgence of interest in the structural arena is evident, while new ways to utilize the interesting electromagnetic properties of SiC continue to increase.

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