InP based HEMTs

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High Electron Mobility Transistors (HEMT), also known as HFETs or modulation doped Field Effect Transistors (MODFETs), is a form of field effect transistor, which is capable of providing high levels of performances at microwave frequencies.

Keywords: High Electron Mobility Transistors (HEMT) ; InP ; modulation doped Field Effect Transistors (MODFETs)

1. Introduction

The high electron mobility transistor (HEMT) was first demonstrated by Takashi Mimura and colleagues at Fujitsu Labs in 1980 [1]. The HEMT based on the concept of modulation doping was first demonstrated by Ray Dingle and collaborators at Bell Labs in 1978 [2]. Beneficial of the development of band gap engineering, a modulation-doped structure creates two-dimensional electron gas (2-DEG) systems at the interface between two kinds of III-V compound semiconductors of different band gaps. The 2-DEG shows outstanding electron transport characteristics in HEMT, making the device suitable for high speed circuit application. Over the last three decades, HEMTs have been demonstrated in several material systems such as AlGaAs/GaAs, AlGaN/GaN [3][4] and InAlAs/InGaAs [5]. HEMTs are mainly available in two flavors-pseudomorphic HEMT (pHEMT) and metamorphic HEMT (mHEMT) [6][7]. Nowadays, with the cost cut down, HEMTs are more widely used in the mobile telecommunications as well as a variety of microwave radio communications links, and many other RF design applications.

2. InP based HEMT

InAlAs/InGaAs HEMTs on InP substrate, also called InP based HEMT, show outstanding low noise and high-frequency and high power added efficiency characteristics [8]. They are the first transistors in material systems, which simultaneously exhibit current gain cut off frequency (ft) in excess of 600GHz and maximum oscillation frequency (fmax) values in excess of 1THz [9]. Increasing the content of InAs in InGaAs alloy largely improves the electron transport properties and increases conduction band discontinuity which results in enhanced carrier confinement at the interface (channel). InP based HEMTs are promising devices to gain ultrahigh-speed operation because of their large carrier concentration and high carrier mobility achieved by this system of material. Nowadays, the demand for the high frequency transistors is becoming greater because the work frequency of high speed applications is becoming higher and higher, such as high-frequency wireless systems, satellite communications, high-speed optical-fiber communication system, critical semiconductor IC applications and so on. Since InP-based high electron mobility transistors (HEMTs) show excellent low noise and ratio frequency performances, therefore, they are considered as the key components for Monolithic Millimeter-Wave Integrated Circuits (MMICs), furthermore, they have obvious advantages in the application of low noise amplifiers at extremely low temperature [10].

InP based HEMT devices are fabricated by epitaxial structure on semi-insulated InP substrate. From bottom to top, the epitaxial structures are usually InAlAs buffer layer, InGaAs channel layer, InAlAs isolation layer, Si δ doping layer, InAlAs barrier layer, InP etch stopper layer and InGaAs cap layer. The heterojunction in InP based HEMT devices is formed by δ doping InAlAs layer and undoped InGaAs layer: the donor impurity Si in the InAlAs layer releases electrons which are transferred from the wide band gap InAlAs side to the narrow band gap InGaAs side to form two dimensional electron gas (2DEG). The transferring process realizes space separation between 2DEG and Si atoms, which increases the carrier concentration in the channel and reduces the influence of the donor impurities on transporting carrier. Therefore, carrier mobility in InP based HEMTs is very high, which makes the devices have obvious advantages in high-speed circuits. The InAlAs isolation layer is helpful for the complete separation of ionized impurities and 2DEG in space. The function of InAlAs buffer layer is to realize the transition from InP layer to InGaAs layer, which relieves the stress caused by lattice mismatch between the substrate and the channel and prevents the defects of substrate from extending to channel. T shape gate usually forms Schottky contact with InAlAs barrier layer or InP etch stopper layer.

3. Working Principle

The working principle of InP based HEMT is very similar with Metal Oxide Semiconductor Field Effect Transistor (MOSFET): when the gate voltage is zero, the Fermi levels in the barrier layer and the channel layer are balanced thus a certain concentration of 2DEG is formed in the channel, so the traditional HEMT device is normally on; When the gate is negatively biased, the Fermi level in barrier layer rises up while the Fermi level in channel falls, the concentration of 2DEG in channel begins to decrease until zero. Oppositely, when the gate is positively biased, the Fermi level in barrier layer falls and the Fermi level in channel rises, so the concentration of 2DEG increases until it reaches a saturated value.

4. Research Progress

Due to the continuous development of the gate technology of InP based HEMTs from 1980s to 2020s, gate length of the device has been reduced from 1 μm to 25 nm. Up to know, the maximum transconductance of InP based HEMTs can reach 3000 ms/mm, the maximum ft can reach 703GHz, and the maximum fmax can reach 1.5THz [11]. The leading international researching institutes for InP based HEMTs include Northrop Grumman, Massachusetts Institute of Technology (MIT), Nippon Telegraph & Telephone (NTT), Chalmers University of technology, etc. Apart from shortening the gate length of device, many other methods can be tried to fully improve the frequency performance of InP based HEMTs, such as inserting a thin InAs layer into the channel InGaAs layer to form a composite channel to increase In content in the channel thus improving the carrier transport characteristics in the channel, optimizing the ohmic contact technology to reduce the contact parasitic resistance of the device; reducing the gate recess width (i.e. the distance between source and drain) to effectively reduce the on state resistance and improve the response delay of the device [12][13][14]. In the foreseeable future, InP based HEMT will always be the solid-state three port device with the highest cutoff frequency.

References

1. Mimura T , Hiyamizu S , Fujii T ; et al. A New Field-Effect Transistor with Selectively Doped GaAs/n-AlxGa1-xAs Heterojunctions. Japanese Journal of Applied Physics 1980, 19, L225-L227, doi:10.1143/JJAP.19.L225.
2. Dingle, R.; Störmer, H.L.; Gossard, A.C.; Wiegmann, W. Electron mobilities in modulation-doped semiconductor heterojunction superlattices. Applied Physics Letters 1978, 33, 665–667, doi:10.1063/1.90457.
3. Khan, M.A.; Kuznia, J.N.; Van Hove, J.M.; Pan, N.; Carter, J. Observation of a two-dimensional electron gas in low pressure metalorganic chemical vapor deposited GaN-AlxGa1−xN heterojunctions. Applied Physics Letters 1992, 60, 3027–3029, doi:10.1063/1.106798.
4. Asif Khan, M.; Bhattarai, A.; Kuznia, J.N.; Olson, D.T. High electron mobility transistor based on a GaN-AlxGa1−xN heterojunction. Applied Physics Letters 1993, 63, 1214–1215, doi:10.1063/1.109775.
5. Cheng, K.Y.; Cho, A.Y.; Drummond, T.J.; Morkoç, H. Electron mobilities in modulation doped Ga0.47In0.53As/Al0.48In0.52As heterojunctions grown by molecular beam epitaxy. Applied Physics Letters 1982, 40, 147–149, doi:10.1063/1.93018.
6. Kim, D.-H.; del Alamo, J.A. 30-nm InAs Pseudomorphic HEMTs on an InP Substrate With a Current-Gain Cutoff Frequency of 628 GHz. IEEE Electron Device Letters 2008, 29, 830–833, doi:10.1109/led.2008.2000794.
7. Hoke, W.E.; Lemonias, P.J.; Mosca, J.J.; Lyman, P.S.; Torabi, A.; Marsh, P.F.; McTaggart, R.A.; Lardizabal, S.M.; Hetzler, K. Molecular beam epitaxial growth and device performance of metamorphic high electron mobility transistor structures fabricated on GaAs substrates. Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures 1999, 17, doi:10.1116/1.590707.
8. Wang, L.-D.; Ding, P.; Su, Y.-B.; Chen, J.; Zhang, B.-C.; Jin, Z. 100-nm T-gate InAlAs/InGaAs InP-based HEMTs with fT = 249 GHz and fmax = 415 GHz. Chinese Physics B 2014, 23, doi:10.1088/1674–1056/23/3/038501.
9. Mei, X.; Yoshida, W.; Lange, M.; Lee, J.; Zhou, J.; Liu, P.-H.; Leong, K.; Zamora, A.; Padilla, J.; Sarkozy, S.; et al. First Demonstration of Amplification at 1 THz Using 25-nm InP High Electron Mobility Transistor Process. IEEE Electron Device Letters 2015, 36, 327–329, doi:10.1109/led.2015.2407193.
10. Ajayan, J.; Nirmal, D. A review of InP/InAlAs/InGaAs based transistors for high frequency applications. Superlattices and Microstructures 2015, 86, 1–19, doi:10.1016/j.spmi.2015.06.048.
11. Ajayan, J.; Nirmal, D.; Ravichandran, T.; Mohankumar, P.; Prajoon, P.; Arivazhagan, L.; Sarkar, C.K. InP high electron mobility transistors for submillimetre wave and terahertz frequency applications: A review. AEU—International Journal of Electronics and Communications 2018, 94, 199–214, doi:10.1016/j.aeue.2018.07.015.

12. Ruiz, D.C.; Saranovac, T.; Han, D.; Hambitzer, A.; Arabhavi, A.M.; Ostinelli, O.; Bolognesi, C.R. InAs Channel Inset Effects on the DC, RF, and Noise Properties of InP pHEMTs. IEEE Transactions on Electron Devices 2019, 66, 4685–4691, doi:10.1109/ted.2019.2940638.
13. Li, Z.; An, N.; Zeng, J.; Tong, X.; Wang, W.; Li, Q.; Liu, H.; Liang, Y.; Tang, H.; Xiong, Y.-Z. Studying on source/drain contact resistance reduction for InP-based HEMT. Microwave and Optical Technology Letters 2016, 58, 217–221, doi:10.1002/mop.29531.
14. Yun, D.-Y.; Jo, H.-B.; Son, S.-W.; Baek, J.-M.; Lee, J.-H.; Kim, T.-W.; Kim, D.-H.; Tsutsumi, T.; Sugiyama, H.; Matsuzaki, H. Impact of the Source-to-Drain Spacing on the DC and RF Characteristics of InGaAs/InAlAs High-Electron Mobility Transistors. IEEE Electron Device Letters 2018, 39, 1844–1847, doi:10.1109/led.2018.2876709.