Epitaxial Growth of Compound Semiconductors Using MOCVD (Ⅲ)

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GaAs-based semiconductor devices have been widely used in the front-end part of wireless telecommunication appliances such as handy phones, in order to support very high-speed data receiving and transmission. This paper reviews the requirement for p-HEMT switch ICs for the control of multi-band/multi-mode handy phone set, the market demand for which is increasing, and the design/manufacturing technology of the epitaxial substrate for the p-HEMT.

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Introduction

The development of equipment that uses wireless communication in personal computers, game machines, music players and consumer electronics has been remarkable in recent years. Furthermore, various types of high-speed, high-capacity wireless communication technology, starting with the next-generation of wireless broadband networks that make possible large volume data communication during high speed transfers as well as wireless HDTV signal shared among consumer electronics devices such as TVs and HDDs have been achieved one after another recently. In the future, we will not only incorporate these technologies into various equipment, but will also incorporate information from the many sensors installed in our living environment through the development of these various types of devices and mainstay networks that support them. Alternatively, we can think in terms of advancement towards the achievement of a ubiquitous society supported by convenient, simple information control through the advancement of active mechanisms deployed in the same manner.

The most popular type of wireless equipment and the one that continues to make remarkable progress at present is the mobile phone. Even though the rate of dissemination has already reached a saturating level in the developed countries, the communications functions, such as connecting with various kinds of media, are continuing to progress, and on the other hand, dissemination in BRICs and the developing countries connected with them is growing rapidly. **Fig. 1** shows actual results and predictions[1)] for the number of wireless handsets and the market for RF modules according to Navian Inc., but the forecast is for a high growth rate over the next five years in the number of wireless handsets, which are estimated to have already exceeded 1

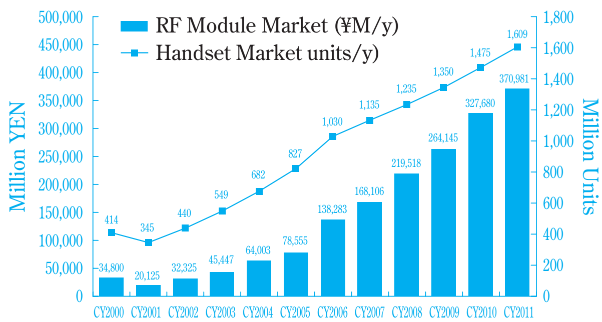

Fig. 1 Market of Wireless Handset and RF Module; Market Change (<2007) and Forecast (>2007) ; Estimated by Navian[1)]

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billion in number, drawn up by the more advanced functions and the increasing rate of dissemination in the group of emerging countries mentioned previously-with their growing populations.

Several standards, such as the Global System for Mobile Communications (GSM) and Code Division Multiple Access (CDMA) coexist in parallel at present. Furthermore, even within the same standard there are multiple frequency bands that can be used, and the number of newer and more advanced mobile phones that can handle these multiple frequency bands and communication modes, that is the so called multi-band/multimode devices, is increasing. Furthermore, wireless communication functions such as wireless LAN and Bluetooth are being added to devices other than mobile phones in some cases. The front end part of mobile phones (and many wireless communication devices) is basically made up of an antenna that transmits and receives radio waves, a receiving section (Rx), including a frequency filter and low noise amplifier (LNA), a transmission section (Tx) that includes a power amplifier (PA), a switch (SW) that switches the Rx and Tx and correspondence between transmitting and receiving as well as other multiple modes, and an RFIC that carries out overall control of the peripheral equipment as shown in **Fig. 2**.[1)]

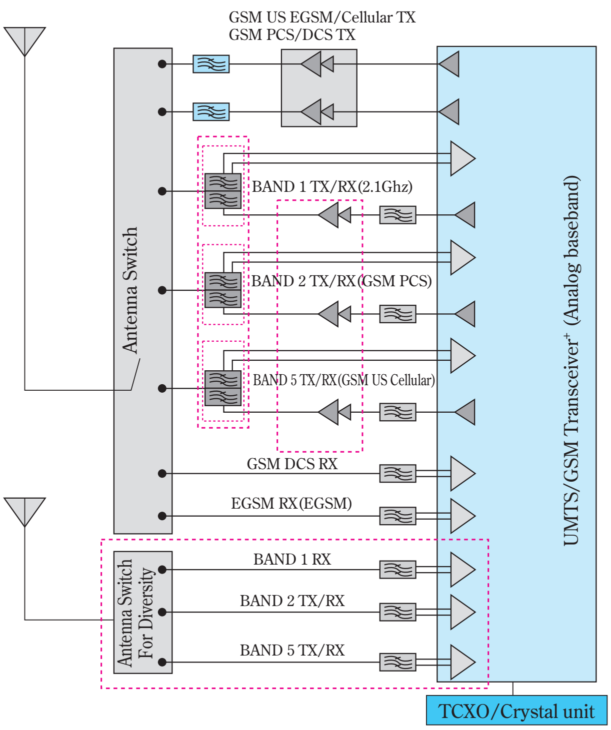


Fig. 2 Schematic Structure of Future UMTS/GSM RF Front End[1)]

In particular, multiple bands (frequency bands) or multiple communication methods (modes) are handled by the multiband/multimode mobile devices shown in Fig. 2, which are expected to increase greatly in number in the future, so there is an Rx and Tx for each band and mode, and the band, mode and transmitting and receiving are switched according to the conditions of use. Multiband/multimode mobile devices of this sort are expected to increase in number in the future, and with increases in the average number of bands and in the number of modes used by each device, the market for the related RF modules is expected to grow even more than for the number of handsets (see the bar graph in Fig. 1).[1)] In the LNA of the Rx sections, the PA of the Tx sections and the switches, which are the principal components used in the front end RF parts, ultrahigh frequencies up to the GHz band are handled directly, so the semiconductors that are used often make use of compound semiconductors which are capable of handling ultrahigh frequencies. Compound semiconductor epiwafers grown by metal organic chemical vapor deposition (MOCVD), which are a Sumitomo Chemical product, are used in the various materials constituting this front end part, but in this paper, we will give an overview of the switches for which recent growth has been particularly remarkable and the so-called p-HEMT epitaxial growth and design technology for switches.

Required characteristics for p-HEMT for switches

Multiple PIN diodes, ICs, etc., that use combinations of multiple PIN diodes and FETs are used in the switches that switch between multiple frequencies, but recently there has been an increase in the use of GaAs FET ICs, which are particularly suited to high frequencies. Since the current consumed during switching is less for GaAs FET ICs than for PIN diode switches, and because GaAs FET IC switches have the characteristics of easy control from a control IC using a voltage signal, they provide the possibility of high-speed switchingand integration of multiple functions and are effective for increasing functionality, reducing size and reducing energy consumption. They are suitable for wireless devices such as small, lightweight mobile phones with limited battery capacity. In particular, their use is rapidly expanding in multiband/multimode mobile devices that need to be highly functional and compact.

The basic concept of a switching circuit using FETs is shown in **Fig. 3**. The switches are placed between the receiving section (Rx), the transmission section (Tx) and the antenna, and the FETs are turned ON and OFF by an input signal to the FET gate, providing a function for switching between receiving and transmitting. With multiband/multimode terminals, the number of Rx and Tx increases in line with the number of bands and the number of modes, so the number of FETs used in switching increases by that amount, and in the IC switches, the large number of FETs is integrated monolithically onto one chip.

The following characteristics are the ones mainly required for FET switch ICs.

A) Low insertion loss in FET circuit path in the ON state
B) High OFF resistance in FET circuit path in the OFF state and good signal isolation between the paths for the various circuits
C) Low distortion characteristics for passing signals
D) High output capability because of high passing signal power
E) Low voltage and low power consumption for the IC as a whole

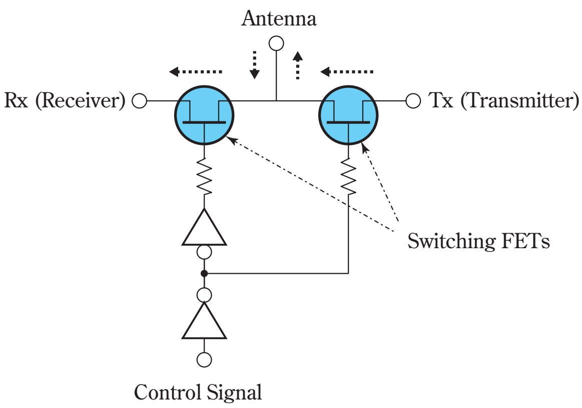


Fig. 3 Schematic Diagram of Switching Circuit

The electron mobility of GaAs is higher than that of Si, and this is advantageous for lowering the ON state resistance. In addition, since a semi-insulating substrate with a large forbidden energy gap and an extremely high resistance can be used, not only can the OFF resistance be raised, but also the parasitic capacitance that inevitably arises between low resistance substrates such as Si and transistor electrodesand interconnections is low, and the loss and leakage of high frequency power arising in both ON and OFF cases through these capacitance components is largely controlled, so intrinsically the high-frequency characteristics are superior. Conventionally ion implantation MESFETs or junction gate FETs where a diffusion method is used have been used in GaAs FETs, but the use of ICs that use so-called heterojunction FETs, of which pseudomorphic high electron mobility transistors (p-HEMT) are typical and which take more advantage of the characteristics of GaAs mentioned above, has increased rapidly in recent times.

We have already commented on the basic structure of p-HEMT and the hetero type epitaxial wafers that are used in their production,[2), 3)] but a brief overview will be given here and an example of the structure is shown in **Fig. 4**. The crystal layer structure of epitaxial substrates for p-HEMT is basically made up of a buffer layer, a channel layer, a electron supply layer/gate layer and a contact layer on a high resistance substrate, and several functional layers are added to this according to the device process or crystal growth process. The first characteristic point and merit of p-HEMT versus conventional GaAs-FETs is the use of a so-called modulation doping structure. The doping layer where impurities are added and the channel layer where electrons flow are separated spatially, and impurity scattering, which is a large factor in electron scattering, is suppressed to a great extent. Regardless of the fact that there is a high current density, it is possible to maintain a high electron mobility, and the insertion loss for the FET when it is ON can be reduced. In addition, the electron mobility of the channel layer is higher than that of GaAs, and by using an InGaAs layer with a larger saturat electron velocity, it is possible to make further improvements to this characteristic. In addition,

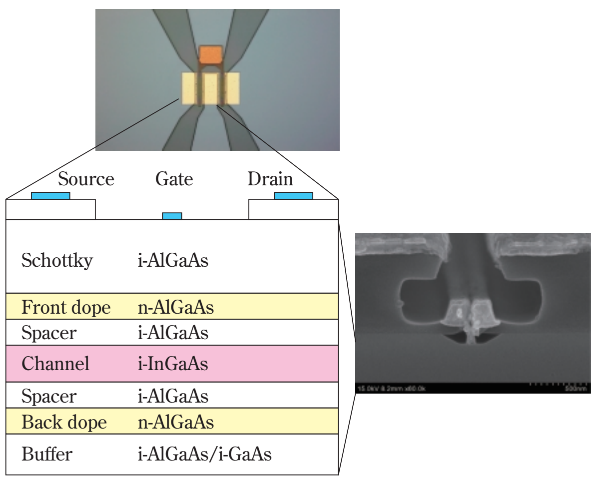


Fig. 4 Structure of p-HEMT

the second point is being able to use AlGaAs which has a large band gap in the gate layer (including part of the collateral electron supply layer) and the buffer layer.

Therefore, the gate breakdown voltage, which determines the limiting voltage due to avalanche breakdown, can be higher, and high output power can be handled along with the high current density described above.

In the design of multilayer epitaxial crystals for p-HEMT, the rough film thickness, composition and doping concentration are first determined in accordance with the threshold voltage necessary for the switch operation and for establishing the transistor circuit, and further fine tuning is carried out to assure the characteristics required for the various types of switches described above.

In the following, we will discuss the main details of the required characteristics for switches and the crystal design and epitaxial growth technology for these while keeping in mind these basic structures.

p-HEMT crystal characteristics and design and control of them for switches

1. Pinch-off characteristics and controlling them

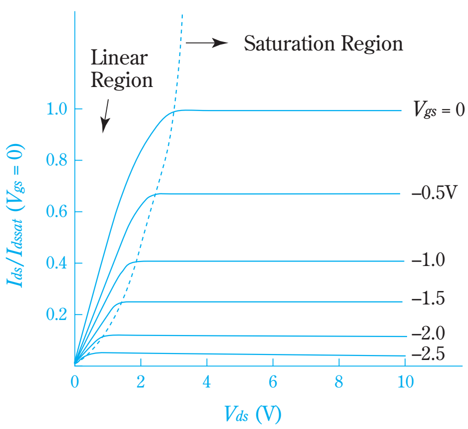
The drain voltage dependency for the drain current with gate voltage as a parameter for p-HEMT is shown in **Fig. 5** (a). In addition, Fig. 5 (b) plots the log of the drain current versus the gate voltage with the drain voltage as the parameter this time.

In Fig. 5 (a) and (b), the maximum value for the drain current is related to the maximum power that can be handled by the switch along with the voltage the gate can withstand. On the other hand, the minimum value is the leakage current during the OFF operation, and reduction of this leakage current (increasing the OFF resistance) is important for assuring the isolation of the other circuit paths in the OFF state from the signal passing through one circuit path when that circuit path is in the ON state during switch operation. In addition, when high frequency signals are handled in the OFF state at this time, a loss arises through the residual capacitance during the OFF state. In GaAs switches that use high resistance semi-insulating substrates, the fact that the parasitic capacitance arising from the use of substrates such as Si, for which increasing the resistance is difficult, is so small that it can be ignored has already been discussed and is one important merit of GaAs switches. However, the small residual capacitance is related to signal distortion, and since it is an important design factor in actual use of GaAs switches, it will be discussed in the following.

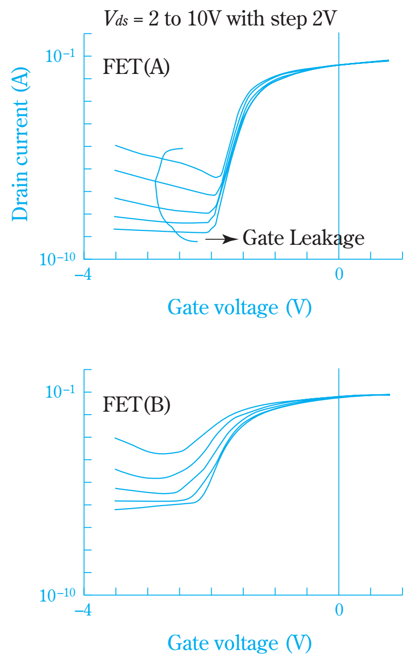
At Linear Region, I_{ds} can be described;

$$I_{ds} = \frac{Z}{L_G} \mu_n C_i (V_{gs} - V_{th}) \cdot V_{ds}$$

L_G : Gate length Z : Gate width
μ_n : Electronmobility
C_i : Gate capacitance
V_{gs} : Gate voltage V_{th} : Threshold voltage



(a) I_{ds} vs. V_{ds}



(b) log I_{ds} vs. V_{gs}

Fig. 5 I-V Characteristics of FET

With p-HEMT produced in the normal manner, the residual current in the part on the lower left shown in the upper graph in FET (A) in Fig. 5 (b) is basically determined by the reverse leak current through the gate, and in mobile phone operations it is normally of a sufficiently low level, but the design and material properties of the lower parts of the crystal layer forming the p-HEMT, that is, the buffer layer and substrate, are insufficient, and so the residual current level cannot be reduced even when the gate potential moves to the negative side as shown in the lower graph FET (B) and Fig. 5 (b). These so-called pinch-off characteristics not only consume unnecessary power, but also makes for a loss in isolation characteristics for the switch. As has already been described in detail in previous reviews[2), 3)] the threshold voltage value for p-HEMT transistors is substantially determined by the film thickness and composition of the epitaxial crystal under the gate electrode and the doping impurity distribution. Theoretically, it is possible to design charge distribution in this cross-section below the gate and the gate electric field dependency by making calculations based on the parameters described above, and it is possible to get highly precise agreement with the actual threshold voltage values for transistors. At this time, it is important to increase the control precision and increase the control on undesirable pinch-off characteristics as described above, but this is a problem of controlling the residual impurities in the substrate and unintentionally doped crystal and microscopic uniformity in the epitaxial crystal as a whole.

(1) Effects of residual impurities and controlling them

We have already described the residual impurity characteristics of MOCVD grown GaAs epitaxial crystals in detail,[2)] and meticulous consideration must be given to the raw material gases and residual contamination in the reaction equipment. In particular, the raw material gases directly affect the crystal quality, so we have put effort into detailed analysis of them and realizing higher purity. In particular, through efforts to lower the silicon compounds and oxygen compounds in organic metal raw materials,[4)] which are typical impurities, and the germanium impurities in the arsine raw material,[5), 6)] it is now possible to obtain these raw material gases industrially and stably such that there is no problem in practical use. On the other hand, with mixed crystal systems that include Al, as in AlGaAs, which have multiple uses in p-HEMT epi substrates in particular, it is easy for crystal contamination to arise because of residual oxygen, silicon, etc., in the crystal growth environment, separate from the raw materials because Al is highly reactive. In GaAs, oxygen forms Ga-O-As interstitial defects, where oxygen is inserted between the Ga and As, or so-called off-site defects, where oxygen substitutes for As positions in the unit lattice and Ga-O-Ga bonds are shifted by two Ga atoms, while two dangling bonds are left in the two remaining Ga atoms. The former are inactive electrically and are thought of as being a stable state. Most of the oxygen actually existing in the GaAs is presumed to be this inactive type. On the other hand, the latter is existing in some proportion as a metastable state, working as both an electron trap and a hole trap in the forbidden energy gap and giving rise to deep active defect levels. They are known to have various effects on semiconductor characteristics.[7)] This bonding state has been made clear through fine structure analysis based on the Ga isotope effect of infrared absorption spectra based on the Ga-O bonds. On the other hand, in AlGaAs, the spectral fine structure is lost because of the alloy effect of the Al and Ga mixed crystal, and detailed analysis cannot be done, but it is presumed that similar off-site defects and interstitial oxygen defects will arise because of the strong bonding energy of Al and oxygen and the confirmation of both electron and hole traps also being formed at a high density in the same manner in AlGaAs:O systems. There have been actual reports of high densities for both traps.[8), 9)] Off-site defects cause deactivation of the donor or acceptor impurities that have been intentionally doped, and they have many undesirable effects on crystal control for electronic devices, which require precise doping control.

Ffor silicon, on the other hand, besides finding contamination that can be thought of as being caused by the residual silicon oxide, organic silicon compounds, etc., from the substrate surface and chamber environments, the silicon that is in the quartz and stainless steel materials that are frequently used in the reaction equipment are also one source of contamination.

Some of the silicon taken up by AlGaAs bonds with oxygen taken up at the same time and is inactivated, but the other is activated as a donor, lowers the insulating properties of the buffer layer and frequently causes current leakage like that in FET (B) at the bottom in Fig. 5 (b), degrading the OFF characteristics of the p-HEMT. Therefore, not only the raw materials in

AlGaAs systems, but also the selection of materials used in the reaction equipment and the preprocessing must be given sufficient consideration.

In MOCVD AlGaAs crystals where these extrinsic impurities and impurities in the raw material gas have been sufficiently eliminated, the final crystal purity is determined by the carbon acceptors. When the raw material organic metals are thermally decomposed, the type of molecule finally absorbed is thought to be monomethyl gallium or monomethyl aluminum, and it is thought that in the end, CH_4 is generated and leaves through the reaction with active hydrogen supplied at the same time from arsine.[2] However, reflecting the high Al-C bonding energy in AlGaAs, residual carbon acceptors are present at 10^{15} to 10^{17} per cm^3, 1 to 2 digits higher than that for GaAs under normal crystal growth conditions. Therefore, it is not easy to obtain AlGaAs crystals of high purity and with high resistance as in the case of GaAs, but when used as a p-HEMT buffer layer, it is possible to control the leakage of channel electrons to the buffer layer by a type of pn junction electric field formed between the n-type doped layers in the vicinity of the channel layer and a p-type buffer layer using these residual carbon acceptors, and this is useful for improving the pinch-off characteristics. The concentration of residual carbon acceptors can be controlled precisely by the Al composition, the growth temperature and the partial pressure of arsine, and the pinch-off voltage value and OFF resistance of transistors using this can be controlled accurately.

(2) Isolation between devices and oxygen doped buffer technology

In terms of the effect of residual impurities and the pinch-off characteristics, it is as has already been described, but we will discuss Sumitomo Chemical's oxygen doped AlGaAs buffer technology a little here. As was discussed in the section above, oxygen is easily taken up in the AlGaAs crystal, and a deep level is formed in the forbidden energy gap. Since this has an effect on donor or acceptor doping control, it is typically thought of as a harmful impurity, but it exhibits very interesting characteristics for some applications.

One of those characteristics is the versatile behavior of the deep level in the forbidden energy gap formed by the oxygen, as both an electron trap and a hole trap. As has already been mentioned, one of the advantages of GaAs is obtaining a high resistance, semi-insulating substrate. Because the forbidden energy gap of GaAs is wide at 1.4 eV and the intrinsic Fermi level for the semiconductor comes near the center of the forbidden energy gap, the carrier concentration due to thermal excitation at room temperature is sufficiently low, keeping its insulating properties. However, mixing in a small amount of residual impurities cannot be avoided with realistic materials technology, and it is not easy to keep good insulating properties with pure non-doped crystals. Therefore, what is empirically used is a compensation technique. For example, in single crystal GaAs substrates, carbon acceptors are introduced into the crystal at $10^{16}/cm^3$ by controlling the carbon concentration in a crystallization atmosphere given a certain extent of high purity for GaAs. At the same time, donor type inherent defects (EL2) with a deep electron trap level around the center of the forbidden energy gap are formed with more excess than the carbon acceptors by surplus pressure of arsenic and the addition of suitable heat treatment. The variations in the residual donor impurities in a range that does not exceed the carbon concentration and the residual acceptor impurities, where the residual hole concentration due to the residual acceptor impurities in a range that does not exceed (EL2 concentration-carbon concentration) are electrically compensated for through this operation. The Fermi potential is fixed in the neighborhood of the EL2 level (center of forbidden energy gap), and it is possible to obtain a substrate with insulating properties.

On the other hand, with oxygen doped AlGaAs, the oxygen forms deep electron and hole traps in the forbidden energy gap at the same time, so residual donor and acceptor impurities are compensated for in a range that does not exceed the oxygen concentration (more precisely, the active oxygen concentration), and a crystal with high insulating properties can be obtained. As was mentioned above, the bonding energy for oxygen and Al is extremely high, and since the solubility limit of oxygen is high, a maximum of $10^{20}/cm^3$ of oxygen can be introduced into the AlGaAs. When this high concentration of oxygen doped AlGaAs crystal is used in a buffer layer of FET crystals, it has the following characteristics. Firstly, there can be effective compensation for substrate surface contamination during epi growth and residual impurities in the epi crystal because of residual impurities in the reaction furnace regardless of the donor/acceptor type. Therefore, FETs with good reproducibility for the substrate surface that tends to arise unstably during actual crystal growth by temporary contamination in the reaction furnace can be realized with stable pinch-off characteristics. The second characteristic is the point that in these highly oxygen doped crystals, the recombination rate for the electrons and holes is extremely fast.

It is known that the oxygen that forms the deep level in the forbidden energy gap works as the effective recombination center, and, for example, this type of oxygen characteristics lowers the luminous efficiency in light emitting devices and has a fatal effect on the devices. On the other hand, however, it also exhibits useful effects such as controlling the increase in the drain current particularly when a high drain voltage is applied under suitable conditions in electronic devices or increasing the insulating isolation properties between FET devices.

It is known that in molecular beam epitaxy (MBE), which is frequently used in epitaxial substrate manufacturing along with MOCVD, under conditions of low temperature and excess As, the so-called LT-GaAs buffer layer introduced a large volume of non-stoichiometric defects including EL2 and exhibited both a high recombination rate and similar characteristics for the FET characteristics.[10] This operating mechanism has not been explained clearly, but because of an extremely fast recombination rate, it is presumed that the electric field distribution in the FET device, which changes according to the leakage and scattering of these excess carriers in the crystal, is stabilized because of the rapid annihilation of the excess electrons and holes generated and scattered in the high electric field in real FETs. These characteristics are extremely useful in improving the OFF resistance and isolation characteristics, which are important characteristics for FET switches, and in FETs with high density integration.[8), 11), 12)] They are widely used in the epi substrates for Sumitomo Chemical's p-HEMT for switches.

(3) Effects and control of microscopic fluctuations in characteristics

As has been discussed up to this point, the pinch-off characteristics are intimately related to the residual impurity concentration in the buffer layer, and another point is that from the standpoint of practicality, an important problem is assuring microscopic uniformity in the crystal material. It goes without saying that macroscopic uniformity in the crystal in semiconductor wafers is directly tied to the yield in semiconductor devices.

In MOCVDs, the main parameters of epitaxial crystal film thickness, composition and concentration of the impurities are determined by the gas flow in the CVD reaction furnace and the diffusion flux and decomposition reaction rate. With the advances in CVD technology, the uniformity in the wafer surface of these main parameters has reached a good value of ± 1% in a 6 inch wafer today. Normally, the threshold voltage for FETs (or p-HEMT) is determined by the thickness, composition and impurity concentration of the crystal under the gate electrode.

Typically, the chip size for p-HEMT ICs which are used in the microwave range is several mm square or lower, but the microscopic uniformity is a micro-crystal uniformity problem that can arise in single minute chips of this sort and not cause a problem in the macroscopic distribution described above.

The epitaxial crystal film thickness, composition and impurity concentration are usually measured using various types of evaluation probes or evaluation devices of several hundred μm to several tens of mm. In actual fact, these parameters have several micro distributions according to the statistical or non-statistical fluctuations, and what is actually measured is an average value within the surface area of the probe, so a deviation may arise with the actual device characteristics because of the device structure and size. For example, when there is a doping concentration where the doping impurity is around $10^{18}/cm^3$, which is frequently used, there is a distribution of one atom for approximately 40,000 atoms of the host crystal, but instead of there being one atom distributed in a three-dimensional crystal with a 10 nm side, there is a distribution within the crystal with a fixed statistical distribution. In VLSIs where the shrinkage of design rules is advancing, the variations in the FET characteristics are also controlled by this statistical variation in the end. This is one of the limiting phenomena in semiconductor devices, but with current p-HEMT ICs, we must consider crystal incompleteness in a slightly larger area. As an example, we will discuss the microscopic crystal morphology of the InGaAs crystal layer making of the channel layer in p-HEMT.

On the surface of the GaAs semiconductor crystal there is an atomic step structure with a minimum step of approximately 0.28 nm, and during epitaxial growth, the crystal growth proceeds in the so-called step flow mode, where the steps move forward where the atoms that are diffused and supplied through the gas phase are taken up at the step site after surface diffusion. In InGaAs, as we have already explained ,[2] multiple atom steps may aggregate and give rise to very large steps with a height of several nm because of large In surface diffusion length (step bunching phenomenon), and the flatness may be lost in comparison with GaAs or AlGaAs. In addition, in InGaAs layers of this type, the InGaAs composition distribution has been found to be spatially nonuniform because of the segregation of In. In addition, when a GaAs or AlGaAs layer is applied on top of this InGaAs layer, the surface atom step structure transitions to the step structure peculiar to GaAs or AlGaAs gradually through a small transition layer, but the large roughness of the InGaAs surface cannot be filled in, and reaches the vicinity of the interface where the gate electrode is formed in the FET while being offset a little each time in the direction of step progress. This situation is shown schematically in **Fig. 6**, it can be seen that at the several points indicated by arrows in the figure, the film thicknesses for the AlGaAs layer and InGaAs layer fluctuate.

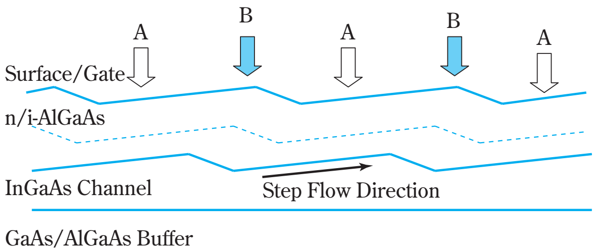
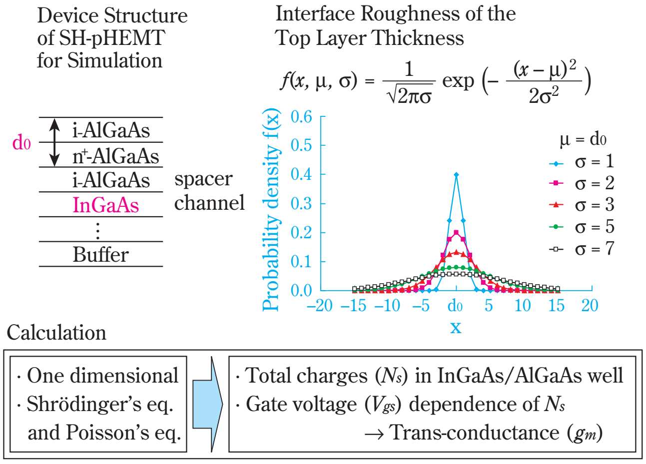
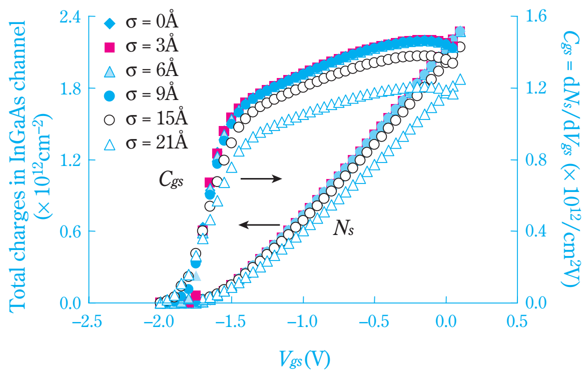


Fig. 6 The Motion of Macro-Step Flow of AlGaAs/InGaAs Hetero Epitaxial Growth

The following phenomena arise if a gate is formed on this crystal when manufacturing p-HEMT. Firstly, at the point shown by arrow A in the figure, the thickness of the AlGaAs (electron supply layer) film is small, so the pinch-all threshold value shifts towards the positive side for the transistor. On the other hand, at the point of arrow B, the thickness of the AlGaAs (electron supply layer) film is large, the pinch-off threshold value is offset to the negative side for the transistor. Therefore, even when the same voltage is applied to the gate in the same transistor, the pinch-off characteristics differ according to the crystal position, and the behavior of the channel current for the electric field under the same gate differs depending upon the location. To deal with this phenomenon quantitatively, we can think of a statistically distributed model that assumes an assemble of minute parallel p-HEMT connections with the gate width a for one p-HEMT being extremely small, with the standard deviation from a prescribed average value for the thickness of the AlGaAs (electron supply layer) film forming each minute p-HEMT (see **Fig. 7** (a)) Fig. 7 (b) is the current-voltage characteristics for a virtual p-HEMT manufactured based on this model shown with the standard deviation for the thickness of the AlGaAs (electron supply layer) film as a parameter.



(a) Modeling of Microroughness in p-HEMT



(b) Impact of Microroughness on p-HEMT ; Calculation Results

Fig. 7

When the standard deviation value is zero, that is when there is a completely uniform crystal, the basic characteristics of the minute p-HEMT and the assembled p-HEMT characteristics are in agreement. However, as the standard deviation rises, the threshold value moves to the negative side, and it can be seen that the reduction in the maximum current value and the reduction in the slope of the current value to the gate voltage value become remarkable.

In this situation, there is a break in the correlation of the characteristics of the designed crystal with the average value as the standard and the characteristics of the p-HEMT device that is actually fabricated. It is difficult to obtain the prescribed device characteristics such as pinch-off characteristics and current value. This is a phenomenon that actually arises with p-HEMT that do not have a good microscopic smoothness, and particularly when roughness arises on the crystal surface, multiple crystals with different physiochemical properties are connected and improvement of the microscopic morphology of the hetero-epitaxial crystals that are produced is an important problem in crystal engineering.

Typically, the microscopic morphology of representative crystals in the surface step structure under certain fixed crystal growth conditions (temperature, pressure, types of gas, partial pressure for raw materials, their mixture, etc.) has a shape peculiar to the type of crystal and composition. With an increase in the Al composition, AlGaAs has a reduction in the average surface atom diffusion length over GaAs, and the step interval is reduced. On the other hand, with an increase in the In composition in InGaAs, the average surface atom diffusion length increases, and the step interval increases. In addition, the step interval changes because of impurity doping. An ideal crystal growth mode would make the step shape president all on the substrate GaAs surface match the shape of the step for the epi crystal growth layer that has a different composition and impurity concentration, but when the epi growth crystal surface diffusion length is shorter than the surface step interval for the base substrate, a three-dimensional nuclear growth arises in the terrace part between step edge and step edge. On the other hand, when the epi growth crystal surface diffusion length is too long, it causes an aggregation of the steps themselves, and as a result three-dimensional roughness accelerates in either case. Therefore, in hetero-epitaxial crystals, of which p-HEMT is representative, there is a need for broad investigations into substrate selection, optimization of the AlGaAs layer, InGaAs layer and GaAs layer that make up the epi layer and interface control technology for mutual transition of the growth conditions for the various crystal layers. **Fig. 8** is an example of an atomic force microscope image of the surface morphology of a InGaAs channel layer for p-HEMT investigated in this manner.

Compared with a crystal formed by a typical method

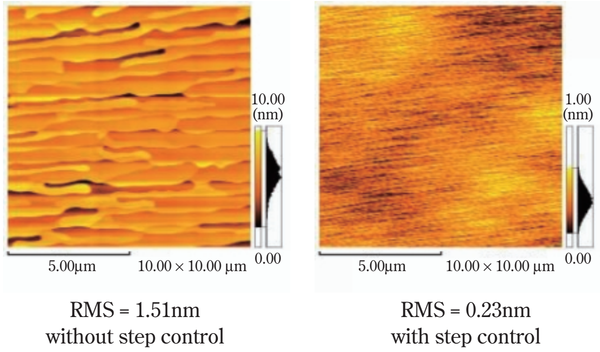


Fig. 8 AFM Image of The Surface of InGaAs Channel in p-HEMT

(left side of Fig. 8) the step of flow is controlled, and in the optimized crystal (right side of Fig. 8) the deviations in the surface roughness (RMS) are 0.23 nm. It can be seen that this is a value that is close to the atomic step height of the surface of (100) surface GaAs (0.283 nm).

In GaAs/InGaAs single quantum well structures, acute PL emission is observed from the InGaAs well layer that has a narrow half width (**Fig. 9** (a)). In addition, clear transitions between quantum levels are observed in photoreflectance and electroreflectance methods (Fig. 9 (b)), and it can be seen that a high quality InGaAs/GaAs heterojunction crystal layer has been achieved.

In InGaAs p-HEMT formed through control technology of this sort, there is a good microscopic uniformity, so there is extremely good correlation between the epi crystal design values and the actual device parameters,

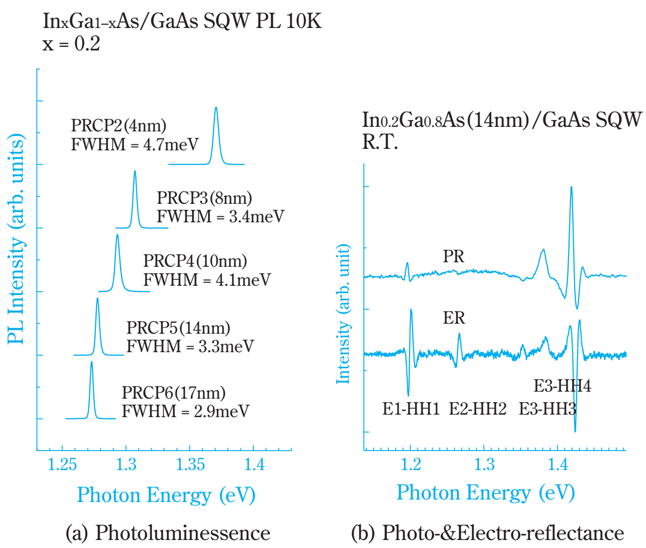


Fig. 9 Optical characteristics of GaAs/InGaAs/GaAs QWs

such as the threshold value in the p-HEMT device. In addition, by increasing the In composition with these crystals, it is possible to achieve a higher electron mobility, which is effective in reducing the insertion loss for the switch used that will be discussed in the following.

2. Reduction of insertion loss and high mobility crystals

Here we will change the subject and discuss an approach from the crystal side for reducing the insertion loss, which is one of the most important problems for switches. In the linear region of the low drain voltage in Fig. 5 (a), the inverse of the rise (slope) of the drain current is defined as Ron (ON resistance), and the insertion loss (IL) during the ON operation of the switch intimately correlates with Ron:

$$\text{IL (insertion loss, dB)} = -20 \log (2\text{Ro}/(2\text{Ro}+\text{Ron}))$$

The effective efficiency PAE' from Tx (power output section) going through the switch has the following correlation with the effective efficiency PAE for the original PA.

$$\text{PAE}' = \text{PAE} \cdot 10 \exp (-\text{IL}/10)$$

This depends on the PAE value, but the reduction in effective efficiency PAE' with any 1 dB reduction in IL reaches approximately 10 to 15%, and the PAE' value is directly tied to battery life when wireless devices are used. In addition, for the Rx (receiving section), the insertion loss in the switch directly correlates with the noise factor for the receiving section, and a reduction of 1 dB in IL makes for an approximately 10% reduction in the coverage area where that device can receive. Therefore, it is extremely important to lower the Ron for p-HEMT when used for switches.

The Ron for p-HEMT can roughly be divided into the components of a) contact resistance in the ohmic electrode for carrier injection and extraction for the epitaxial crystal from the source and drain electrodes, b) lateral channel resistance in the InGaAs quantum well layer that forms the channel and c) vertical resistance from the ohmic electrode injection area to the channel. From the viewpoint of crystal structure, we must determine the forming of methods for the heterojunction interfaces of the crystals with different crystal compositions, concentrations, thicknesses and types while keeping a balance with the other required characteristics to minimize these various components. However, we will give a detailed discussion of improving electron mobility in the channel InGaAs layer, which is the greatest factor affecting Ron and for which there is little trade-off with the other required characteristics.

As in the equation for the drain current and drain voltage in Fig. 5 (a), Ron is defined by the inverse of the slope in the linear area of the low drain voltage region in the figure, and is simply expressed by:

$$\text{Ron} \propto L_g/(\mu_n \cdot C_i \cdot Z)$$

and with conditions of the same gate dimensions (gate length (L_g) × gate width (Z)), is inversely proportional to gate capacitance (C_i) and electron mobility (μ_n). In the case of p-HEMT and MOSFET, C_i is proportional to the secondary electron density induced in the channel layer, and the higher this is the better it is for Ron, but as a result of the fact that the gate charge and discharge capacitance that accompanies ON and OFF also increases, it causes an increase in power consumption, and an increase in electron mobility is most preferable as it doesn't affect the other characteristics.

The electron mobility is determined by the effective mass of electrons in the material making up the channel and the scattering factor when the electrons run through the channel. In terms of the scattering factor, there is scattering due to thermal vibration (phonon) of the crystal lattice, crystal scattering due to the random distribution of constituent elements present when there are mixed crystals and other factors determined by the materials, as well as impurity scattering, scattering due to the microscopic roughness of the interface that has already been discussed and other factors that can be controlled by crystal growth technology and epitaxial layer design. InGaAs is used as the channel material in p-HEMT, and compared with the normal HEMT with GaAs channels, the effective electron mass is small, that is, essentially we can expect the electron mobility to be high. The energy difference between the InGaAs layer and the n-type AlGaAs layer that forms the electron supply layer and the lower end of the conductance band is high, so as a result of the quantum wells that form the channels being deep, the channel electrons are effectively held in, and there is the characteristic of not being able to receive impurities scattering due to ionized donors present in high densities in the n-type AlGaAs layer. Actually, the latter

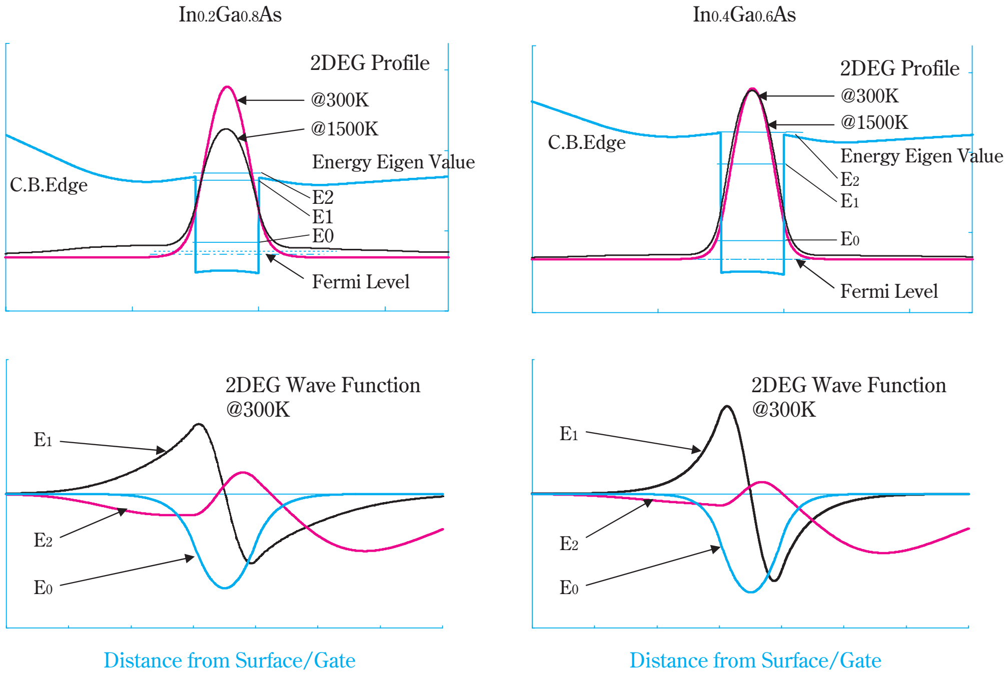


Fig. 10 The Spatial Distribution of 2DEG Density and Wavefuction in p-HEMT

effect can be confirmed by quantum mechanical calculations. **Fig. 10** shows the relationship between channel thickness and InGaAs composition for electron distribution in standard selectively doped InGaAs channels. With increases in the In composition, the penetration of the electron distribution that arises in a small amount into the AlGaAs side becomes smaller, and we can see that the electrons are confined in the InGaAs channel effectively. Furthermore, when we examine the wave function at this time, the wave function which is generally contained in the channel at the ground level continues to move up to the first excitation level and second excitation level, and we can see that the situation is one where spreading happens easily on the AlGaAs side. The electron distribution in Fig. 10 is the value at equilibrium at room temperature, but the actual electrons in the channel are accelerated by the electric field in the transistor, so they are thought to be transporting while rising to a higher excitation level. This suggests the superiority of InGaAs channels which can effectively confine electrons with a higher order excitation, particularly high In concentration channels.

In addition, to avoid a drop in mobility because of the scattering of ionized donors for the small amount of electrons that penetrate into the electron supply layer in actual p-HEMT crystals, a non-doped spacer layer is typically inserted, but in high InGaAs channel crystals, there is little electron penetration, so the spacer layer film can be thin, with higher concentration electron supply layer doping possible. This corresponds to being able to raise this two-dimensional electron concentration in the channel more effectively, and in p-HEMT design, it is effective for improving the maximum current value or gate breakdown voltage while maintaining a fixed transistor threshold voltage.

Therefore, we examined the mobility characteristics in combination with an actual selectively doped structure in InGaAs crystal quantum well systems where epitaxial growth is carried out while controlling the surface step structure as has already been discussed. During the doping, a double hetero structure was set up where Si doped n-type AlGaAs was arranged above and below the InGaAs crystal layer, and the characteristics were being able to obtain a high two-dimensional electron density of 2.2 to 2.4 × $10^{12}/cm^2$. The electron mobility at room temperature when the composition of the strained InGaAs layer used for the channel was changed is shown in **Fig. 11**.

The triangles in Fig. 11 are the data with conventional crystals where step bunching reaching several nm arises without step control being carried out during InGaAs layer growth, and a drop in the mobility is found with an increase in the In composition. On the other hand, those circles show where step control is applied, and the crystal roughness in the vicinity of the

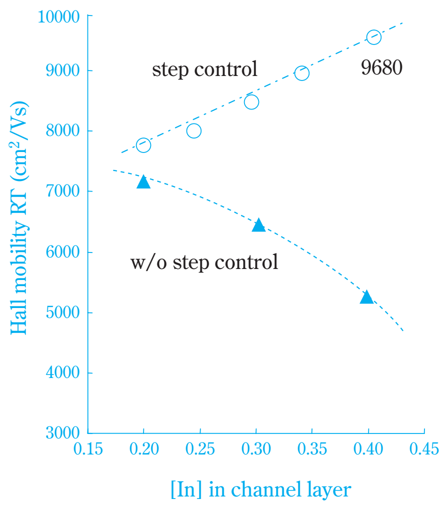


Fig. 11 Electron Mobility of 2DEG in Selective-doped DH-AlGaAs/InGaAs

channel interface is controlled to 0.3 nm or less, where the crystals were grown under equivalent conditions as those of QW growth where the clear quantum wells structure shown in Fig. 9 and the effective mass that is smaller than GaAs were confirmed by photoreflectance measurements.

In the step controlled crystals, the mobility increased with an increase in the In composition, and at an In composition of 0.41, it reached 9680 cm^2/Vsec. Generally, in addition to normal impurity scattering and phonon scattering in crystals such as InGaAs, there was a drop in mobility due to the effects of mixed crystal scattering because of the random distribution of group Ⅲ elements (In and Ga in this case), and an increase in the mobility arose at the same time because of a reduction in the effective mass, so the mobility that is actually observed had a somewhat complicated behavior. However, in the data in Fig. 11, a high mobility that clearly exceeds the mobility of GaAs at an In composition of 0.3 or greater is observed. In particular, the mobility described above at an In composition of 0.41 has a value higher than any reported values for two-dimentional electron mobility for GaAs and strained InGaAs on GaAs substrates observed at room temperature up to now as far as the authors know. Along with this substantiating the results of measurements using electroreflectance where the actual effective electron mass in InGaAs was small in strained QW structures, there is the large practical significance of the point that characteristics close to expensive InP substrate lattice matched InGaAs systems were obtained using conventional p-HEMT device process technology all on GaAs substrates, which are used widely in industry.

3. Distortion characteristics and improvements in linearity problems

Finally, we will touch briefly on distortion characteristics, which are important for switches. It is ideal for the amplification characteristics of the power amplifiers in the transmission sections to be linear, but in actual fact, linearity is lost because higher harmonic waves arise in the output sections where high-efficiency operations are possible. With power amplifiers, the linearity is already greatly improved by various types of distortion correction technology, but if the linearity of the circuit that includes the transistors that formed a switch when the signal passes through that switch is poor, the problem of distortion arises. In addition, for example, in WCDMA systems, interference of signals occurs within different frequencies with the transmission side Tx and receiving side Rx passing through the switch because of an effect known as mutual intermodulation distortion between signals with different frequencies.

In any event, in the neighborhood of the limits of communications for this device, for example, when the transmission energy increases and the receiving energy decreases, the intermodulation can be made to arise with signals from other devices, and problems arise with connections, so strict standards have been established for the amount of this distortion.

In the OFF side FET, the residual capacity is not constant for the voltage applied to this FET, and since there is a small voltage dependency, it causes a higher harmonic power leak through that residual capacity, causing a nonlinear effect to arise for the distortion characteristics in the switch. In particular, with multifunction switches that handle multiple bands and multiple modes, there is one FET in the ON state and all of the other FETs are in OFF the state. Since a large number of FET residual capacities are connected in parallel and combined, the effect is not small. The residual capacity and its voltage dependence at this time is thought to be mainly dependent on the spatial charge density accompanying the doping of the semiconductor layers in the vicinity of the gate part and its distribution, and the contribution of the shape and circuit design utilized in the device is large, but by calculating the related residual capacities using numerical calculations and fine tuning the film thickness, composition and impurity profile so as to minimize the applied voltage dependency, improvements can be made to a certain extent.

On the other hand, in the ON side FET, the linearity of the current value for the applied voltage with a low electric field is an important indicator.

In commercial GaAs FETs, linearity is not always better than conventional PIN switches. **Fig. 12** shows the electron velocity dependency over a wide range of electric field intensities in GaAs.

The first differential coefficient of the electron velocity curve in Fig. 12 (figure on the left) (dashed line) corresponds to the mobility, and the fast rise of the electron velocity in a low electric field in GaAs originates in high mobility. However, while the electron velocity rises rapidly in GaAs, it suddenly drops after reaching a peak at a certain electric field. This is intimately related to the GaAs band structure (figure on the right in Fig. 12), and along with the highly mobile electrons with a small effective mass normally positioned in the Γ band making the transition to a high energy state because of electric field acceleration, the result is a transition to the L band which has a large state density and heavier effective mass with a low mobility and is positioned approximately 0.29 eV higher than the Γ band, through phonons scattering. The aspects of this nonlinearity based on the band structure vary according to the type of semiconductor, and in particular, the difference in energy between the Γ band and the L band is considered to be an important factor. **Table 1** gives an outline of the physical parameters for the typical semiconductors.

The difference in energy between the Γ band and the L band in InAs is a large at 0.78 eV, and it is larger than that for GaAs. Since for InGaAs the difference in the Γ and L band is thought to be increased by linear interpolation it is expected that the transition rate to the L band would be relatively low in high In composition channel structures such as those shown in the previous section, but the actual correlation between the In composition and the ON side FET linearity is a problem for verification in the future.

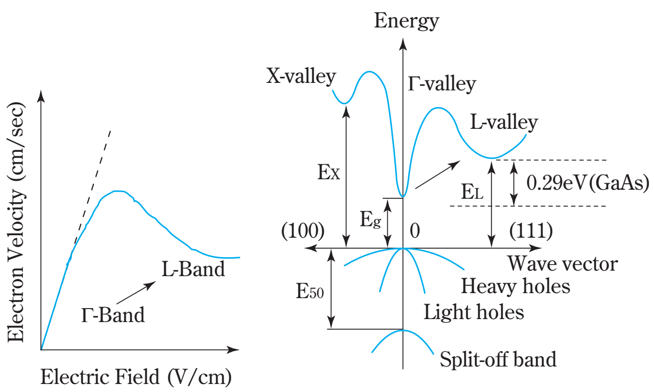


Fig. 12 Band Structure and Non-Linear Electron velocity at High Electric Field

Conclusion

We have given an overview of p-HEMT switches for which use is increasing because of developments in wireless communications equipment mainly on mobile phones recently and the recent technology for epitaxial wafers used in these. Technically, effort needs to be put into further reductions in ON resistance and improvement in distortion characteristics to further improve performance and reduce chip size, but we can expect the market for p-HEMT switch ICs, with their superior basic characteristics and ease-of-use for integrated circuits to expand in the future. In addition, this paper did not touch upon it but p-HEMT has a superior potential for LNA and PA, and the expectations are great for p-HEMT for other main components making up these front end parts.

Table 1 Electron and hole mobility and other typical physical parameters of various semiconductors

	Si	Ge	GaAs	InGaAs(In=0.5)	InAs	InP	InSb
Electron Mobility@RT	1,500	3,900	8,500	11,000	33,000	6,000	80,000
Electron effective mass	0.98(X)	0.082(L)	0.065	0.045	0.023	0.077	0.0135
Hole Mobility@RT	450	1,900	420	–	460	150	1,700
Hole effective mass	0.16(lh) 0.49(hh)	0.04(lh) 0.28(hh)	0.082(lh) 0.45(hh)	0.053(lh) 0.43(hh)	0.024(lh) 0.41(hh)	0.12(lh) 0.56(hh)	0.016(lh) 0.438(hh)
Energy Gap(eV)@RT	1.12(indirect)	0.66(indirect)	1.42	0.89	0.36	1.35	0.18
$\Delta E_{\Gamma\text{-}L}$(eV) of conduction band	–	–	0.29	0.54	0.78	0.50	1.67

Si, Ge : Ref.13), GaAs, InAs, InP, and InSb : Ref.14)
InGaAs(In=0.50) : electron mobility : experimental data, other parameters : interpolated from GaAs and InAs

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