Design and Analysis of GAIVBE System and Application to the Growth of Semiconductor Thin Films

- On the Growth of GaAs on Si -

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Abstract

A single-crystalline epitaxial film of GaAs has been grown on Si using a gas assisted-ionized vapour beam epitaxial technique. The native oxide layer on the silicon substrate was removed at 550℃ by use of an accelerated arsenic ion beam, instead of a high-temperature desorption. During the growth the substrate temperature was maintained at 550℃. Transmission electron microscopy and electron diffraction data suggest that the GaAs layer is an epitaxially grown single-crystalline layer. The possibility of growing device quality GaAs on Si is also demonstrated through fabrication of GaAs MODFET on Si substrates.

I. Introduction

In common practice today, there are several material growth techniques that are particularly suitable for the sequential growth of epitaxial thin films, which are required for the fabrication of compound semiconductor optoelectronic device structure. In general, these techniques can be classified into three different categories : Molecular-Beam Epitaxy (MBE)[1~4] Vapor Phase Epitaxy(VPE)[5~7] and Liquid Phase Epitaxy(LPE).[8~10] Described in this paper are the preliminary results from yet another thin-film growth technique, known as Gas Assisted Ionized Vapour Beam Epitaxial (GAIVBE) deposition,[11] which has been employed to grow an epitaxial GaAs thin film on Si.

GAIVBE deposition is a technique which shares the advantages of " conventional" beam-assisted deposition, but may overcome some of its limitations. Although the actual mechanisms of GAIVBE deposition have not been elucidated, it is believed that they are similar to in beam deposition in that energy is supplied to the growing film surface by an ion beam thus allowing for localized atomic motion and rearrangements. There is, however, an important difference. The energy of an ionized cluster is shared by all atoms in the cluster so that individual atom energies are very low even when the individual clusters themselves contain substantially high energies. Thus, sufficient energy can be supplied to a localized region to stimulate atomic motion, but without any one atom gaining sufficient energy to become implanted or to create point defects. In principle, therefore, GAIVBE deposition offers a novel way to produce thin films, and for some applications, it may have important advantages over conventional MBE or beam-assisted deposition methods.

The application of GAIVBE deposition to the growth of high-quality films has, indeed, been demonstrated. Sung and coworkers have shown, for example, that epitaxial Al_2O_3 films could be grown on Si at temperatures as low as room temperature.[12] They have reported other successes with a variety of source materials and substrates ; these include metals, intermetallic compounds, semiconductors, oxide, nitrides, carbides, fluoides, and even organic materials.[13~14]

In most of this work, the main objective was to produce highly adhesive, smooth coatings; although with a few materials, the Sung's group was also able to grow thin films of controllable crystalline structure and optical properties.[14] In spite of these apparent "successes," the work of Sung et al. has been controversial ever since it was first reported in 1972, mainly because they have failed to characterize their cluster beams for size and energy distribution determining what films can be grown on what substrates, the conditions of growth, and very importantly, the quality of the films and the perfection of the interfaces.

Our work with GAIVBE's at the University, which began just over ten years ago, has concentrated mainly on

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compound semiconductors, metals with known applications in microelectronics, and catalytic materials. The principel objective of this work has been twofold: (i) to study the fundamental physical processes controlling the cluster formation and (ii) to evaluate the unique capabilities, as well as limitations, of the GAIVBE technique for various scientific applications of current interest. The results that we have obtained to date are still preliminary; nevertheless, by growing an epitaxial GaAs film on Si at a low temperature using dual-beam configuration, by producing Zn and Al clusters, and by fabricating crystalline catalytic Ni particles having sizes in the range 10-1000Å, we have clearly demonstrated that the GAIVBE technique is both promising and versatile.

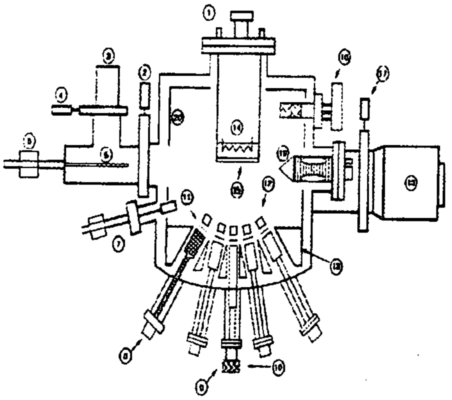
Presented in this paper is an account of the work on the growth of GaAs thin films on Si using the GAIVBE deposition and the electrical characteristics of GaAs MODFET fabricated in the GaAs on Si wafer.

The apparatus, specifically designed and fabricated for the present work, and the experimental procedures used are described in Sec.2. The results obtained with the apparatus are presented and discussed in Sec.3, along with the microanalysis results of the grown films. Section 4 contains the summary and concluding remarks.

II. Experimental Apparatus and Procedures

The GAIVBE deposition system specifically constructed for the present study is shown in Fig.1. Two separate crucibles, one for As and the other for Ga, are used to independently control the temperature of the source material in each crucible. In this respect, GAIVBE is similar to MBE. The similarity between GAIVBE and MBE, however, stops here since in GAIVBE the crucible is covered with a cap having a small flow-constricting nozzle which allows one to maintain a much higher vapor pressure inside the crucible than that of MBE. It is because of this nozzle that the vapor coming out of the crucible adiabatically expands into a vacuum resulting in small aggregates of atom, namely, "cluster". Once produced, these clusters are impact ionized using thermionic electrons, accelerated in an electric field, and delivered to a heated substrate for material deposition. The ratio of ionized to neutral clusters in the ionized cluster beam, the energy with which the ionized clusters impinge upon the substrate, the size of clusters, and the substrate temperatures then become the parameters controlling the morphology, smoothness, and other properties of the growing film.

The GAIVBE system schematically illustrated by Fig.1 is housed in a vacuum bell jar whose base pressure was typically 5×10^{-7}Torr for all the thin-film growth runs. A typical experimental sequence for the growth of GaAs on Si is as follows. First turn on the As crucible and heat the substrate to the desired temperature. Then turn on the ionizer and supply an acceleration field to the ionized As beam so that, when the energetic beam hits Si substrate, it can remove the native SiO_2 layer. The energy of the As beam and the time duration over which it is directed onto the substrate therefore control the substrate cleaning. While cleaning is being done start heating the Ga crucible. The next step is to start the film growth process by lowering the As beam acceleration voltage to a desired value and opening the shutter to the Ga crucible. The GaAs thin films grown on the Si substrate using these procedures are shown and analyzed in the next section.



① substrate maipulator ② neumatic valve ③ turbo molecular pump 60 l/s ④ gate valve ⑤ load-lock ⑥ magnet coupled feedthrough ⑦ flux monitor ⑧ E-beam unit ⑨ plasma unit ⑩ rf matching circuits ⑪ shutter ⑫ ionizer & accelerator ⑬ LN2 shroud ⑭ heater ⑮ substrate ⑯ 1600 l/s turbo molecular pump ⑰ gate valve ⑱ quadrapole mass analyzer ⑲ RHEED gun ⑳ LN2 shroud

Fig. 1. Schematic of a dual-crucible GAIVBE system employed for the growth of an epitaxial GaAs thin film on Si.

III. Experimental Results and Discussion

1. The growth of GaAs on Si

GaAs thin films grown on a Si substrate under two different conditions are presented. Fig. 2(a) shows a scanning electron microscopy(SEM) picture taken of a sample (sample A) prepared at an As crucible temperature of 300℃, a Ga crucible temperature of 920℃, an As ion acceleration voltage of 1kV, and a substrate temperature of 550℃. The Si substrate used was an n-type (100) oriented Si wafer. The nozzles that served as the exit end of the source crucible were 1-mm diameter × 2-mm length for both the As and Ga crucibles.

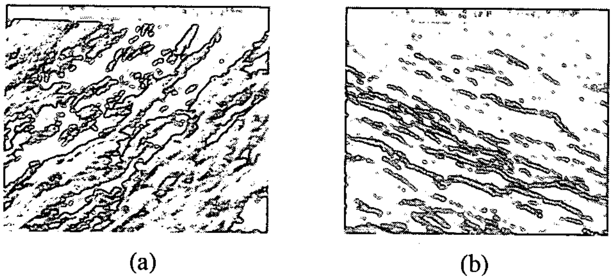


Fig. 2. SEM pictures of two GaAs films on Si grown under different conditions. The magnification is 10k×. (a) Sample A : Prior to the growth, the Si substrate was heated to and kept at 900℃ for 15min. (b) Sample B : Prior to the growth, the Si substrate was cleaned for 1h using a beam of As ions of As accelerated to 1.5kV.

The SEM picture of Fig.2(a) includes that the grown film is fairly smooth; however, x-ray diffractometer measurement (not presented) and a cross-section transmission electron microscopy(TEM) analysis[Fig.3(a)] indicate that although it is of a preferred (111) orienation. the grown film is single crystalline. As can be seen from Fig.3(a), there is still a thin layer of SiO_2 remaining on top of the Si substrate.

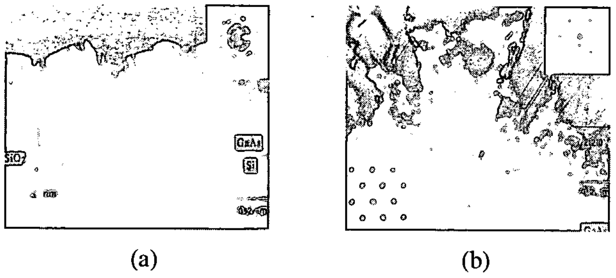


Fig. 3. TEM bright-field images of GaAs on Si for the samples shown in Fig.2. (a) Sample A: An enlarged micrograph (lower left-hand inset) shows that inadequate cleaning (utilizing a high-temperature thermal desorption) leaves a SiO_2 layer about 30Å thick along the GaAs/Si interface As a result, GaAs deposited on becomes polycrystalline (upper right-hand inset). (b) Sample B: After the SiO_2 layer is removed by ionized As′flux, single-crystalline epitaxial GaAs layer is deposited on Si substrates successfully.

As a result, GaAs was actually nucleated and grown on an amorphous substrate. Given the complete freedom in the nucleation orientation on an amorphous substrate, as most other cubic materials which are deposited on amorphous substrates do, the obtained GaAs on Si exhibits a columnar growth shown in Fig.3(a) with a (111) preferred orientation.

To remedy this drawback, an attempt to remove the native oxide layer at a low substrate temperature was made by using an ion beam accelerated to 1.5kV. The GaAs thin film shown in Fig2(b) (Sample B) was grown after the Si substrate was cleaned for 1h using an accelerated As ion beam. During this cleaning, the As crucible temperature was maintained at 300℃ and the substrate temperature at 500℃.

The rest of the growth conditions and procedures remained the same as those adopted for the sample shown in Figs. 2(a) and 3(a). The measured growth rate was found to be identical for the two cases.

As can be seen from Fig.2(b), the surface of sample B, albeit imperfect, is smoother than that of sample A[Fig.2(a)]. But more importantly, an x-ray analysis [Fig.4] showed that the orientation of the grown film is (100) same as the substrate. Furthermore, a TEM analysis, as shown by Fig 3(b), indicates that the film is single crystalline and that the native oxide layer is no longer present.

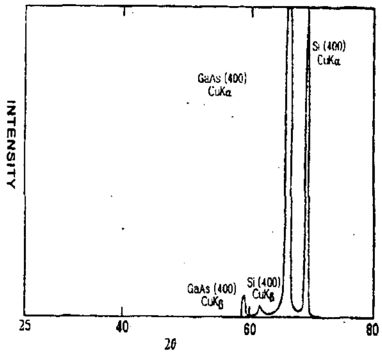


Fig. 4. X-ray diffraction data of sample B [Fig.2(b) and 3(b)] indicating single crystalline (100) GaAs layer grown on (100) Si.

As for the verification of the existence of clusters which may or may not have played an important role in the present work, a statement or two must be made to eliminate any misunderstanding. First of all, a direct cluster measurement was not made in the present work simply because such an apparatus could not be implemented inside the vacuum bell jar that housed the dual-crucible system used for the present work, however, at least two indirect proofs can be offered by way of stating that it was very likely that because of the size of the nozzle and the vapor pressure used for the work, As clusters were present, along with the single atoms, during the growth. The first indirect proof is that using a 2000-amu quadrupole mass spectrometer a beam of Al produced with a nozzle of 1-mm diameter and 2-mm length, same as the one used for the present work, was analyzed and the results showed that clusters as large as 10 atom were produced. Using the same-size nozzle Ni was deposited onto a copper-coated graphite TEM target and the analysis showed that clusters ranging in size from 10 to 1000 Å were produced in abundance.

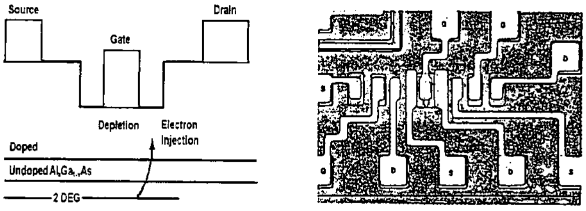
For a detailed study of the GAIVBE technique, there is, therefore, a strong need for a specially designed UHV system, similar to a state-of-the-art MBE system, that provides for convenient production and detection of multiple ionized vapour beam's, controlled ionizations of ionized vapour beam's and determination of their ionization state, tuning of the ionized vapour beam energy, and finally in situ characterization of growing films. This was not done in the work of Takaki and, consequently, that work is highly debated in the film-growth community. Such an UHV system featuring multiple-source flanges, a reflection high-energy electron diffraction (RHEED) diagnostic, a 4000-amu quadrupole mass spectrometer, a load lock, and other auxiliary components have been under construction in our laboratory at University and are near completion. Using this state-of-the-art system, we plan to do in situ studies of various important issues pertaining to film growth with GAIVB's : the size and energy distribution of clusters, the mechanism by which the clusters interact with energetic electrons during their ionization, and the thin-film growth process after a partially ionized cluster beam has been delivered onto the substrate.

2. *The Electrical Characteristics of GaAs MODFET on Si*

Although both the MODFET and MESFET are in general terms similar (majority carrier devices), there are same important distinctions between them. The two principal differences are that first the electrons in a MODFET are confined to an interface where a 2 DEG is formed, while in a MESFET they are confined to a much larger region and have essentially three degrees of freedom. The second difference is that channel layer of a MODFET is very high purity GaAs as opposed to a MESFET where doping levels in the range of $10^{17}cm^{-3}$ to $10^{18}cm^{-3}$are typically used. Since electrons in a MODFET are closely confined to an interface, any interface roughness is capable of degrading the performance of these structures. Work by Drummond(15) has highlighted the importance of the interface problem. Given the importance of interface quality as discussed above, the problem of obtaining a high performance MODFET on Si can be seen to be a more difficult task than that of MESFET.

In this paper, the electrical characteristics of GaAs MODFET on Si have been studied. This investigation was carried out both because it may reveal some material related deficiencies and because of its technological importance.

The MODFET structures consisted of a 2μm thick GaAs buffer layer, a 30 Å undoped $Al_{0.28}Ga_{0.72}As$ set back layer, a 350 Å doped ($N_D=5\times10^{18}cm^{-3}$) $Al_{0.28}Ga_{0.72}As$ layer, and a 200 Å ($N_D=5\times10^{18}cm^{-3}$) GaAs cap layer. The GaAs/AlAs superlattice was incorporated at the substrate-epi interface and had five periode of 30 Å GaAs wells and 20 Å AlAs barriers. These structures were grown on (100) orientations of Si.



(a) (b)

Fig. 5. Schematic cross section (a) and top view of a GaAs MODFET on Si(b).

After crystal growth devices with $1\times290\mu m^2$ gates and 3μm source-drain spacing were fabricated, alloyed AuGe/Ni/Au contacts were used for source-drain, and Al was used for the gate metal. The GaAs on Si wafers do not require any special handling, and standard GaAs processing techniques were used in fabricating these devices. Fig. 5 shows a schematic cross section and a top view of a fabricated device. Shown in Figures 6 and 7 and are output I - V traces from MODFETs on Si at 300K and 77K. The transconductance of similar devices are as high as 170mS/mm at room temperature and increased to 275mS/mm when cooled to 77K. The absence of looping in the traces of Fig. 6 and 7 the high transconductances indicate the high quality of the GaAs on Si materials reported here.

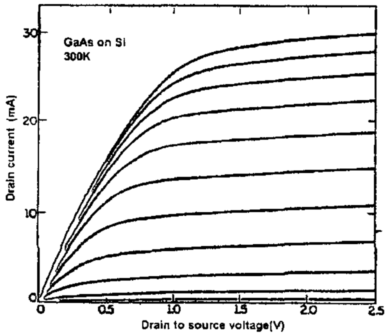
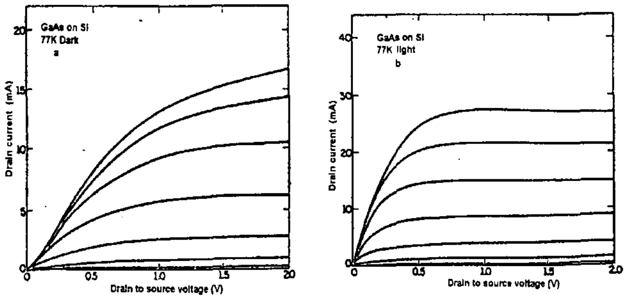


Fig. 6. Output I - V characteristics for GaAs MODFET on Si at 300K(Gate voltages are 0.2V/step from -1.0).

Van-der Pauw-Hall measurements were also done on the MODFET layers grown (100) Si. Hall mobilities of $38{,}000cm^2/V\cdot s$ were obtained at 77K with an associated sheet carrier concentration of $8.3\times10^{11}cm^{-2}$. These results further verify the existence of a high saturation velocity-high mobility 2 DEG and attest to the high quality of the epitaxial layers.

Fig. 8 and 9 show drain saturation current and transconductance versus gate bias for GaAs MODFETs with

$1 \times 145 \mu m^2$ gates on Si substrates. Fig. 8 shows 300K data while Fig. 9 shows 77K data. As can be seen from these figures, maximum transconductances were 153mS/mm and 214mS/mm at 300 and 77K, respectively, on Si.



(a) (b)

Fig. 7. Output I - V characteristics for GaAs MODFET on Si at 77K (a) in dark and (b) in light (Gate voltages are 0.2V/step from -1.0).

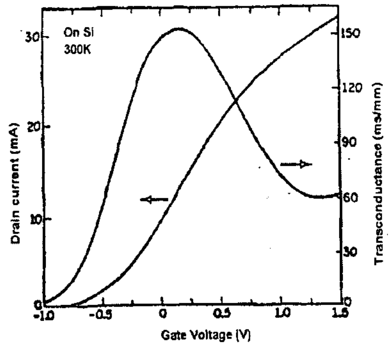


Fig. 8. Drain saturation current and transconductance for a $1 \times 145 \mu m^2$ gate GaAs MODFET on Si at 300K.

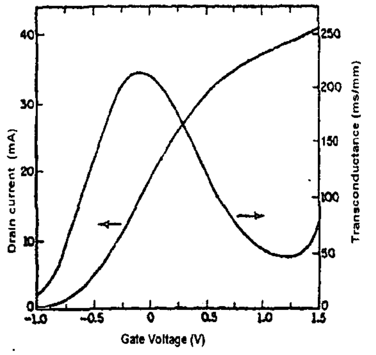


Fig. 9. Drain saturation current and transconductance for a $1 \times 145 \mu m^2$ gate GaAs MODFET on Si at 77K.

These results are very encouraging in that device performance which is nearly state of the art is achieved for GaAs grown on Si while it is yet a relatively immature technology.

Ⅳ. Summary and Concluding Remarks

Preliminary results indicating the capability of the GAIVBE technique to grow an epitaxial thin film of GaAs on Si have been presented. Of particular interest is the demonstration that the native oxide layer can be removed from Si at a low temperature (550℃) using a beam of accelerated As ions. Because of this unique capability, the Si substrate temperature was never raised above 550℃ during the entire film-growth sequence. The issue of whether As clusters played a role, if any, in the present work was not resolved because of lack of appropriate diagnostics, although in conjunction with both the Al and Ni work that was done using different systems, it was observed that clusters could be produced with a similar setup (data not included in this paper). A state-of-the-art GAIVBE system that can possibly resolve this and other fundamental issues, thus facilitating more rudimentary understanding of the GAIVBE technique, has been fabricated and is near completion.

It is hoped that this new UHV system equipped with in situ diagnostics and convenient load lock will in time answer various important fundamental issues pertaining to the GAIVBE technique. These include determining (i) the underlying physical processes of an energetic cluster impinging on a substrate, (ii) the relationship between the physical parameters of the GAIVBE technique - cluster size, energy, ionization state, and substrate temperature and the quality and nature of the film, (iii) the physical processes involved in producing the ionized vapour beam, and (ⅳ) the capabilities and limitations of the GAIVBE method. We will carry out this research by performing studies of the cluster beam characteristics and their relationships to film growth, detailed characterization of the films and film-substrate interfaces, and theoretical studies of the growth process.

The use of Si as a substrate material for the growth of GaAs provides several advantages and new possibilities. First, the growth of GaAs on Si would allow Si integrated circuit to use GaAs devices. In this way, the critical functions could be performed with GaAs while the less critical ones could be done in Si, taking advantage of the high integration densities. Another possibility is the use of GaAs lasers for optical chip communication, reducing the driver requirements. These drivers are at present a major bottleneck in overall system speed. Aside from these new possibilities, these are advantages in using Si substrates for GaAs technology itself. At present GaAs substrates larger than 3″ diameter are not available.

The growth of GaAs on large diameter Si wafers would provide a larger diameter wafer on which to build GaAs ICs. Further, Si has a larger thermal conductivity than does GaAs which would allow higher power dissipation levels. Si is also much less expensive and is mechanically stronger than GaAs, minimizing wafer breakage problems. The absence of looping in the traces of I-V characteristics of GaAs MODFET and the high transconductances indicate the high quality of the GaAs on Si materials. The properties of MODFET devices fabricated in these GaAs layers grown on Si look quite promising.

V. Acknowledgments

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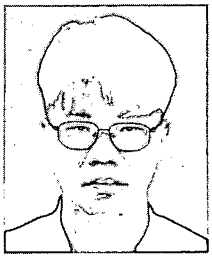

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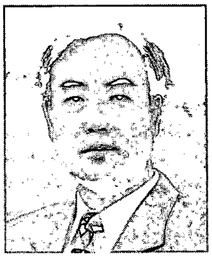

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