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A Novel Lateral Surface Superlattice Structure Utilizing Schottky Barrier Height Control by Doped Silicon Interface Control Layers

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A novel lateral surface superlattice (LSSL) structure was realized on the modulation-doped AlGaAs/GaAs system by forming periodic arrangement of surface Schottky barriers with different Schottky barrier heights (SBHs) produced by doped Si interface control layers (Si ICLs). Clear oscillations of the current-voltage characteristics due to the quantum effects were observed at 4.2K, showing successful introduction of periodic potential modulation at the heterointerface.

1. INTRODUCTION

Nowadays, many quantum-wave devices and single electron devices are realized by modulating the confinement potential at the heterointerface of the compound semiconductor modulation doped structures from the top surface. Conventionally, this modulation is achieved by the split-gate technique[1,2] which relies on reduction of the surface potential on the air-exposed free semiconductor surface with reference to that at the metal-semiconductor interface. However, the surface state properties of the air-exposed surface are unknown and unstable.

The purpose of this paper is to propose a novel method to introduce potential modulation at heterointerface by Schottky barrier height (SBH) control with Si interface control layers (Si ICLs). In this structure, the surface is totally covered with metal, which enables one to avoid the complexity and uncertainty of the air-exposed free surface of the semiconductor. It also can produce larger amplitudes of potential modulation. In this study, this new method was applied to construction of a lateral surface superlattice (LSSL) which is capable of producing useful negative differential resistance characteristic for high frequency operation according to theoretical prediction.[3,4]

2. NOVEL METHOD FOR MODULATING POTENTIAL

The new potential modulation structure for the LSSL device utilizing the SBH control by doped Si ICL is shown in **Fig.1**. The Si ICL is periodically inserted at the top metal-semiconductor interface formed on a conventional AlGaAs/GaAs modulation doped structure. The fabricated LSSL device has an standard field-effect transistor structure except for the hidden fine structure of the gate shown in **Fig.1**.

The principle for SBH modulation is the following. By inserting an MBE-grown ultra-thin (2nm) Si layer with high As doping at the metal-semiconductor (M-S) interface, ionized donor in the ICL produces strong dipole at interface and reduces the SBH of n-type GaAs. According to previous

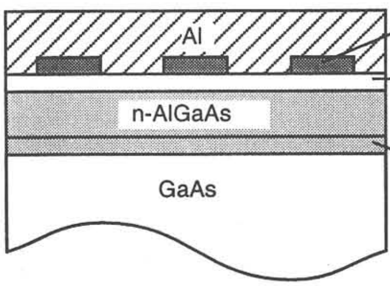

Figure 1. The new potential modulation structure for LSSL.

experiments, SBHs of Al/GaAs with and without As doped Si ICL became about 500meV and 800meV, respectively.[5] Thus, periodic insertion of As doped Si ICL into the Schottky interface should create periodic potential with an amplitude of 300meV at the interface which then modulate the potential at the inner heterointerface.

A two-dimensional potential calculation was performed to investigate the effect of the surface condition on the potential at the heterointerface. **Figure 2** compares the results of computer calculation of potential at the heterointerface for the present LSSL and the split-gate LSSL structures both having a periodicity 200nm. For the split-gate structure, a uniform surface states density of 1.2×10^{12} $cm^{-2}eV^{-1}$ was assumed at the free semiconductor surface. It is clearly seen that larger potential modulation can be obtained with the novel structure. It is also seen that the two types of devices behave differently under gate bias. For present structure, Fermi level position can be controlled more sensitively by the gate bias V_G.

3. EXPERIMENT

The basic Si ICL structure of the LSSL device was formed by using an UHV-based system including a MBE chamber and a metal deposition chamber connected with an UHV transfer chamber. At first, a conventional modulation doped AlGaAs/GaAs structure was grown by MBE. Subsequently, MBE growth of an As doped Si ICL (2nm)

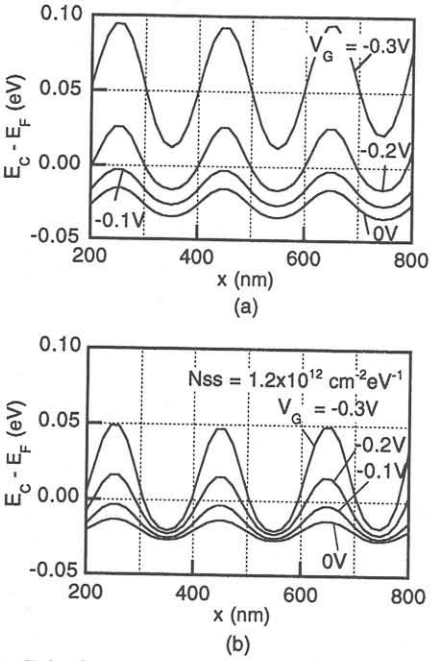

Figure 2. Calculated potentials at heterointerface of (a) the LSSL having controlled Schottky barriers and (b) conventional periodic split gate.

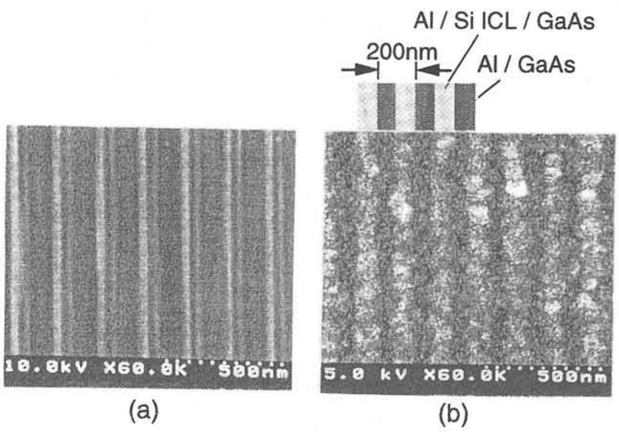

Figure 3. SEM images of (a) the basic pattern of the grating gate and (b) after metalization.

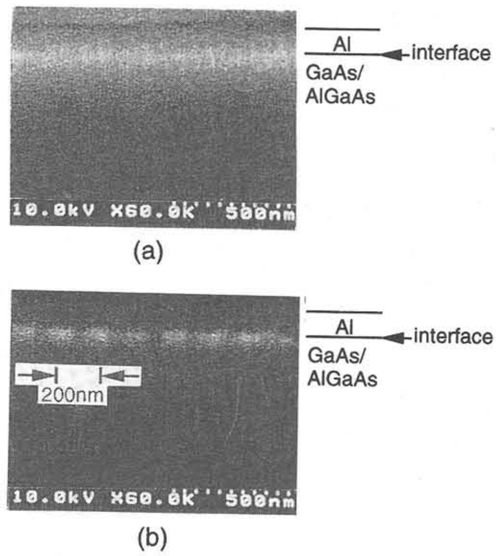

Figure 4. The cross sectional (a) SEM and (b) EBIC images.

was made where As doping was done by irradiation by As flux during growth. Then, the first Al layer was deposited on the Si ICL without exposing the sample to the air. Next the sample was taken out to air, and mesa etching and formation of source drain electrodes were made. Then, Al film with Si ICL was periodically removed by using electron beam lithography and wet chemical etching. Finally, the second Al metal was deposited and the gate electrode was formed. **Figure 3** shows the SEM images of the grating gate **(a)** before and **(b)** after the final metalization. The grating pattern had a periodicity of 200nm.

The drain-source current-voltage (I_{DS}-V_{DS}) and I_{DS}-V_G measurements of the fabricated LSSL devices were done at 4.2K. Electron beam induced current (EBIC) measurements were also done where an electron beam was irradiated on the cleaved surface of the sample, and the generated charge carriers were detected as a current in an external circuit.[6] This measurement was found to be extremely powerful for investigation of the potential in nanometer-scale structures.

5. RESULTS AND DISCUSSION

Figure 4 shows the cross sectional SEM and the EBIC images of the sample having a grating gate using Si ICL. In **Fig.4 (b)**, a periodical EBIC pattern having the same period with the gate is clearly seen whereas no such pattern is observed in the SEM image. This signal is located at the metal/semiconductor interface region. The EBIC measurement demonstrates that a periodic variation of electrostatic potential is produced at the M-S interface by inserting Si ICL.

The fabricated LSSL device showed reasonably good field-effect performance on a macroscopic scale at 4.2K. However, its transconductance was found to possess periodic patterns in low V_{DS} region as shown in **Fig.5**. In spite of its complexity, the positions of peaks and dips remained the same, being independent of V_{DS} and showing a periodicity of 1.7meV.

The I_{DS}-V_{DS} characteristics and the output conductance of the LSSL are shown in **Fig.6 (a)** and **(b)**, respectively. Output conductance oscillation was observed and its period changed with V_G. Such a change of periodicity with gate bias was not observed previously in the split gate type LSSL devices.[1,2] From the interval of the oscillation peaks, the voltage drop per one grating gate was estimated to be 1~2meV, depending on V_G.

The origin of the two kinds of oscillatory behavior can be explained in terms of the sequential resonant

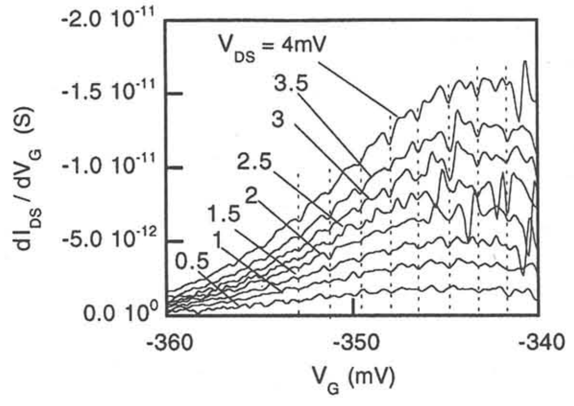

Figure 5. The tranceconductance characteristics of the LSSL.

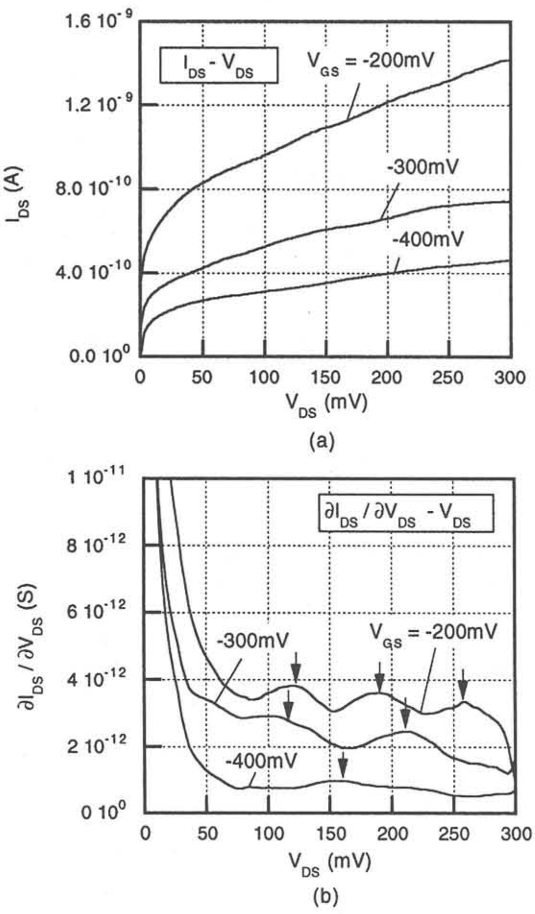

Figure 6. (a) I_{DS}-V_{DS} characteristics and (b) output conductance of the LSSL.

tunneling.[7] Periodic variation of potential results in formation of multiple quantized levels shown in **Fig.7** with possible narrow mini-band formation due to the superlattice effect. Although most of the current flows either by inelastic tunnelling or thermal excitation process, we assume the existence of the process as shown in **Fig.7 (a)** and **(b)**, for oscillation of the transconductance and output conductance, respectively. In **Fig.7 (a)** where V_{DS} is

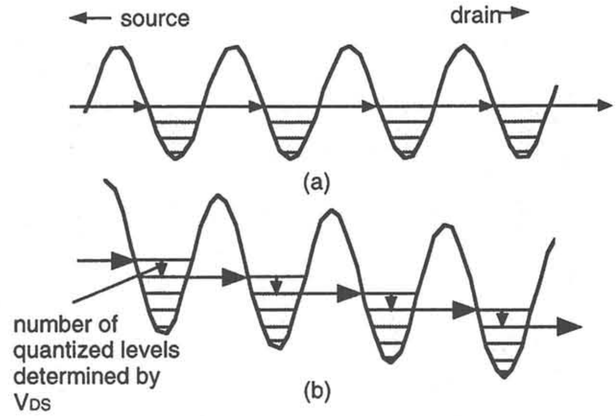

Figure 7. Sequential resonant tunneling model for the observed oscillatory behavior.

sufficient low, the location of Fermi level is controlled by V_G whereas sequential tunneling takes place only when E_F agrees with one of the quantized levels. The observed result that the interval of the oscillation peak is kept constant **(Fig.5)** indicates that the potential modulation is nearly harmonic for occupied states. In **Fig.7 (b)**, where V_{DS} is large, the sequential tunneling takes place with energy loss and it occurs when the loss is equal to energy separation of different quantized levels. The values of energy separation estimated from **Figs.5** and **6 (b)** are about 1-2meV, and they are consistent with the results of calculation shown in **Fig.2 (a)**.

6. CONCLUSION

A new method to introduce potential modulation at heterointerface by Schottky barrier height control with Si interface control layers is proposed and applied to the fabrication of a lateral surface superlattice. The oscillatory behavior in EBIC, I_{DS}-V_{DS} and I_{DS}-V_G characteristics show that the periodic potential modulation was successfully achieved, in spite of extremely thin Si ICL with a thickness of 2nm.

REFERENCES

1) K.Ismail, W.Chu, D.A.Antoniadis and Henry I.Smith, Appl.Phys.Lett. **52** (1988) 1071.
2) G.Bernstein and D.K.Ferry, J.Vac.Sci. Technol. **B5** (1987) 964.
3) H.Krömer, Phys. Rev. **109** (1958) 1856.
4) H.Sakaki, K.Wagatsuma, J.Hamasaki and S.Saito, Thin Solid Films **36** (1976) 497.
5) K.Koyanagi , S.Kasai and H.Hasegawa, Jpn. J. Appl. Phys. **32** (1993) 502.
6) H.J.Leamy, J.Appl.Phys. **53** (1982) R51.
7) K.Ismail, W.Chu, R.T.Tiberio, A.Yen, H.J.Lezec, M.I.Shepard, C.R.Musil, J.Melngailis, D.A.Antoniadis and Henry I.Smith , J.Vac.Sci.Technol. **B7** (1989) 2025.