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Characterization of Potential Modulation in Novel Lateral Surface Superlattices Formed on GaAs Multiatomic Steps

Kazuki Yamatani, Masashi Akabori, Junichi Motohisa, Takashi Fukui
Research Center for Interface Quantum Electronics, Hokkaido University, North 13 West 8,
Sapporo 060-8628,Japan Fax : +81-17-716-6004, Phone : +81-11-706-7172
E-mail : yamatani@ryouko.rciqe.hokudai.ac.jp

1.Introduction

Much attention has been paid to physics and device application of various kinds of quantum nanostructures. To realize such quantum nanostructures, various techniques have been proposed and attempted. Among them, direct formation utilizing self-organized nature of epitaxial growth is very promising, because high density of damage-free quantum nanostructures can be realized mainly by one-step growth. As one method of such technique, we have been reporting on the application of multiatomic steps to quantum structures, which is known to be formed spontaneously during metal-organic vapor phase epitaxial (MOVPE) growth on vicinal (001) GaAs substrates [1]. In particular, we have investigated the electron wave interference effects in lateral surface superlattice (LSSL) [2] utilizing multiatomic steps. However, detailed electronic states in our LSSL is not clarified yet.

The propose of present paper is to clarify the potential profiles in LSSLs using multiatomic steps. We estimated the amplitude of potential modulation by investigating the electron transport across the steps. In addition, potential profile in the channel was investigated by using a quantum point contact.

2.Sample Structure and Experimental Procedure

We grew selectively doped n-AlGaAs/GaAs/AlAs double heterostructure of Fig.1(a) by MOVPE on a vicinal (001) substrate misoriented by 5° toward the $[\bar{1}10]$ direction. During the growth of GaAs buffer layer, multiatomic steps are formed. As this multiatomic step structure is almost preserved during the successive growth of AlAs and GaAs layers, the thickness modulated channel is formed, which give rise to the periodic potential modulation in channel. The detail of the MOVPE growth procedure and conditions is reported elsewhere [2]. An atomic force microscope image of AlAs surface is shown in Fig.1(b) together with its schematic cross section. The period of multiatomic steps is measured to be 71nm. Assuming that these multiatomic steps are ideally formed for both bottom (GaAs on AlAs) and top (AlGaAs on GaAs) interfaces, we expect that the cross section of the channel GaAs layer (average thickness: 15nm) is represented as Fig.1(c). Note that the thickness modulation depends on the amount of lateral growth of GaAs layer which can be controled by the growth conditions. Here the lateral growh rate determined by TEM observation and photoluminescence reported in previous paper [1] is used.

The height of periodic potential V_0 is estimated by assuming that it is given by the difference of quanutized energies between the thickest (18nm) and the thinnest (11nm) regions in the channel. Thus V_0 is estimated to be 17meV. As this approximation apparently overestimates V_0, we will examine V_0 experimentally, as described in the next section.

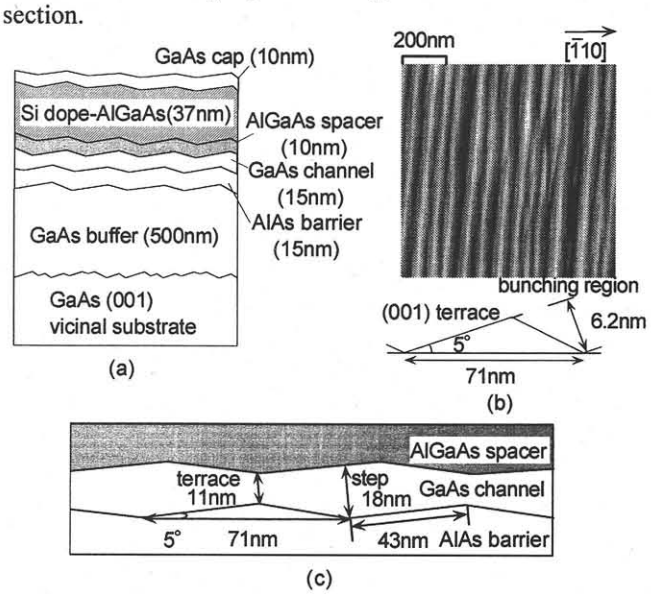

Fig.1 (a) Layer structures of MOVPE grown LSSL. (b) AFM image of AlAs barrier layer surface and its cross-sectional illustration. (c) Schematic cross section of the channel.

3.Estimation of Potential Modulation

We first fabricate a Hall bar with a gate on the epitaxial layer described above. Here the channel is aligned in perpendicular to the multiatomic steps. We measured the magnetoresistance (MR) at 2K to estimate electron concentration. We note here that the MR oscillation was periodic in inverse of magnetic field B for every bias voltages. The results are shown by the solid circles in Fig.2 as a function of gate voltage. One can see that the electron concentration N_S linearly increases as V_G. We estimated the threshold voltage for N_S=0 by the linear interpolation as indicated by the solid arrow in the figure. We also plotted the two terminal conductance of the gated Hall bar as a function of V_G by dotted lines. One can see the onset voltage is much larger than the threshold voltage of N_s. It is noted that such difference was not observed when the channel of Hall bar is parallel to the multiatomic steps. In addition, the mobility $\mu_\perp$ perpendicular to the step is smaller than that parallel $\mu_{//}$ to the steps. Furthermore, $\mu_\perp$ perpendicular to the steps shows more drastic decrease as N_S is reduced,

which is consistent with the results shown in Fig.2. Therefore, the appearance difference in the threshold as well as anisotropic mobility of our LSSL is a clear evidence for the potential modulation induced by multiatomic steps, and suggests the existence of mobility gap for $\mu_{\perp}$.

We estimated the height of potential modulation as follows. The carrier concentration at the onset of current rise estimated to be $1.9\times10^{11}cm^{-2}$. By directly applying the density of states of two-dimensional gas, the Fermi energy at the onset is calculated to 6.8meV, which approximately corresponds to V_0. This value is about one third of the first-order approximation described in the previous section. The reason for this difference is partly due to the crudeness of the approximation used in the both theoretical and experimental estimation, and partly to the deterioration of the periodicity of multiatomic steps, especially at the bottom interface.

4.Potential Profile Probed by Point Contact

In a split gate configuration, applying different bias voltages to two gates can control the minima of the potential. Thus it is possible to investigate the local potential profile in the channel by measuring the conductance through a quantum point contact (QPC) at various gate bias conditions [3,4]. We applied a similar technique to the present LSSL to measure potential profile formed by multiatoic steps. For this purpose, we fabricated QPC (see inset of Fig.3(a)) on the structure of Fig.1(a), and measured the two-terminal conductance of the sample with constant drain bias (V_{DS}=0.5mV) at 1.7K. Here the gate are defined across the steps in order to probe the potential profile across the multiatomic steps.

When the same voltages is applied to two gates, we can see the quantization of conductance in unit of $2e^2/h$, as shown in Fig.3(a) In this figure we subtracted a series resistance of 1.3kΩ, which is very close to thr estimated value(1.1kΩ). These results clearly indicate the ballistic nature of the transport through QPC in our samples.

Figure 3(b) also shows the two-terminal conductance, where only one side of the gate is changed while maintaining the other at the zero bias. Here no correction due to series resistance is made. When only the gate 1 voltage V_{G1} is swept, similar oscillations and plateaus are observed as in Fig.3(a). In addition, the conductance is very small below V_{G1}<0.2V. On the other hand, almost linear dependence is observed for the V_{G2}. This result implies that the region beneath the gate 2 is almost depleted at zero bias conditions, and that the leakage which goes through beneath the gate is a dominant conduction path (not the point contact region) so long as the leakage conductance is smaller than the quantized conductance 2 e^2/h.

Figure 4 also shows the conductance of the sample plateau as a function of V_{G1}. Here, the different curves correspond to different V_{G2} values, which are changed from –0.1V to 0V by 0.01V step. One can see the plateaus around V_{G1}~ 0V, is every V_{G2} condition. However, the width and height of the plateau are slightly changed by V_{G2}. We think these results suggest that the potential profile is not uniform across the channel and contribution of the potential introduced by multiatomic steps in our samples.

References

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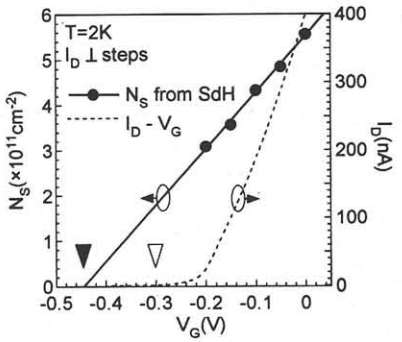

Fig.2 N_S and I_D for the current perpendicular to the steps.

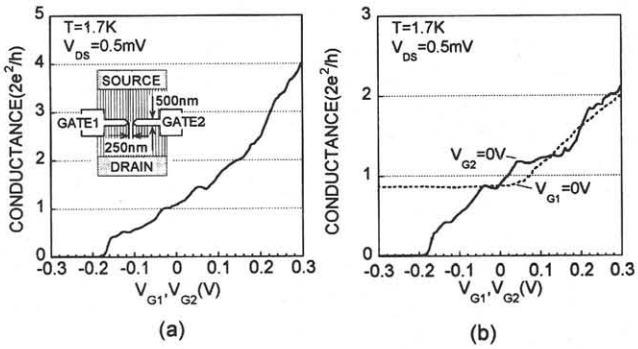

Fig.3 Two terminal conductance through QPC when (a) both gate or (b) one side of the gate is swept.

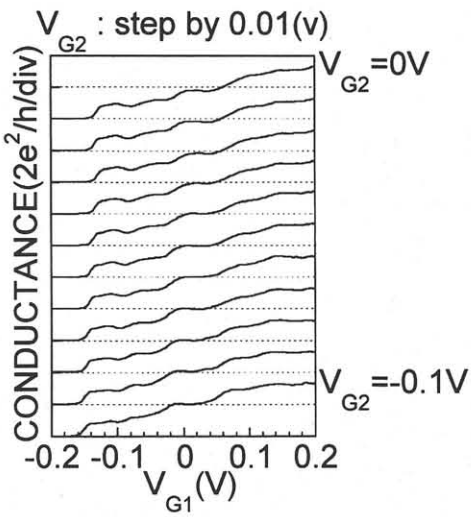

Fig.4 Plot of the conductance through QPC measured for various gate bias conditions.