Analysis of the temperature-induced transition to current self-oscillations in doped GaAs/AlAs superlattices

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Abstract
We observed the decrease of the hysteresis effect and the transition from the stable to the dynamic domain regime in doped superlattices with increasing temperature. The current–voltage characteristics and the behaviours of the domain boundary are dominated by the temperature-dependent lineshape of the electric field dependence of the drift velocity \( V(F) \). As the peak–valley ratio in the \( V(F) \) curve decreases with increasing temperature, the hysteresis will diminish and temporal current self-oscillations will occur. The simulated calculation, which takes the difference in \( V(F) \) curves into consideration, gives a good agreement with the experimental results.

1. Introduction
The formation of electric field domains in weakly coupled GaAs/AlAs superlattices (SLs) exhibits an either stable or unstable domain boundary depending mainly on the carrier density in the SLs [1–4]. The temporal current self-oscillations occur when the carrier density is within a certain range. Above this range the self-oscillations disappear completely, resulting in the build-up of stable electric field domains, while at a lower density a uniform electric field distribution will form in the SL. Actually, several other effects also influence the properties of the domain boundary in SL samples which have a fixed carrier density. For example, a doped SL shows different transport regimes under varying transverse magnetic field [5, 6]. Ohtani et al [7] have investigated the transition between stable and dynamic electric field domain formation in undoped photoexcited GaAs/AlAs SLs and found that the thermal activation enhances the formation of dynamic domains. They explained this phenomenon mainly by the carrier density. In this paper, we show that the properties of domain boundaries are closely related to the lineshape of the electric field \( F \)-dependent electron drift velocity \( V(F) \) for the vertical transport in an SL, especially the peak–valley ratio of the negative differential velocity (NDV) region in the \( V(F) \) curve. The experimental results indicate that a stable domain boundary will switch into unstable condition due to the decrease of the peak–valley difference. The results of our simulation calculation strongly support the conclusion.

2. Sample and experimental details
The sample investigated in this paper was a doped GaAs/AlAs SL grown by MBE in a VGMKII system. The SL sample consists of 40 periods of 14 nm GaAs well and 4 nm AlAs barrier. To reduce the density of interface states, only the central 10 nm of the well was doped with Si (doped density \( N_d = 2 \times 10^{17} \text{ cm}^{-3} \)). The separated energy levels calculated through the Kronig–Panney model are \( E_{\Gamma 1} = 21.5 \text{ meV}, E_{\Gamma 2} = 86.3 \text{ meV}, E_{\Gamma 3} = 198 \text{ meV}, E_{X1} = 115.8 \text{ meV} \) and \( E_{X2} = 163 \text{ meV} \) respectively. An SL diode with an area of 0.01 mm² was made. The current–voltage (I–V) characteristics of the sample were measured from 12 to 200 K with an HP4155A semiconductor parameter analyser. An HP54600A digital oscilloscope recorded the current self-oscillations.
3. Results and discussions

Figure 1 shows the measured $I$–$V$ characteristics of electric field domains at different temperatures ($T$) for up- and down-sweeping directions of the biasing voltage, where only the second plateau of the $I$–$V$ curves is focused because the self-oscillation is too weak to be measured for the first plateau at an elevated temperature. A large hysteresis effect is observed at 12 K. It decreases gradually with increasing $T$ and then almost disappears when the temperature is close to 170 K. Furthermore, the temporal oscillatory structures appear in $I$–$V$ curves, and the length of the plateau becomes shorter with increasing $T$. When $T$ is raised to 200 K, no branchlike structures can be seen in the $I$–$V$ curve except for a broadened peak. The detailed development process of the hysteresis effect with increasing $T$ is depicted in figure 2, where the solid circles and crosses indicate the current at the first peak in the plateau versus $T$ for scanning up and down, respectively. Figure 3 indicates temporal current self-oscillations that occur at $T = 180$ K at voltage ranging from 2.55 to 2.85 V, and the current self-sustained oscillation at 2.8 V is exhibited in the inset. It is noted in figure 2 that the current for sweeping up gradually decreases with increasing $T$ until 140 K, and then rapidly increases. However, for sweeping down, the current is almost constant when $T$ is less than 80 K, and then it rapidly increases with an unchanged slope at higher temperatures. The decrease of the sweeping-up current when $T < 140$ K can be understood by the following formula [8] which describes the sequential resonant tunnelling process between the subbands in SLs:

$$J = en\ell(1 - \exp(-\Delta/kT))\frac{2\hbar|\Omega|^2\Gamma}{(eF\ell - \Delta)^2 + \Gamma^2}$$

where $\Omega$ is the matrix element of the Hamiltonian between the subbands divided by $\hbar$, $\ell$ is the length of one SL period, $\Delta$ is the energy difference between the centres of the neighbouring subbands ($\Delta = 64.8$ meV for the first current peak in the second plateau) and $\Gamma(=\hbar/\tau)$ is the half-maximum width (WHM) of the momentum relaxation. It is noted that $eF\ell - \Delta = 0$ in the case of resonance. When $T < 140$ K, $\exp(-\Delta/kT) \ll 1$. As $\Gamma$ is influenced by the phonon scattering and has a dependence on the temperature, it causes a temperature-dependent change in the peak current, resulting in a decrease of the current for the sweeping-up direction according to equation (1). The rapid increase of sweeping-up current for $T > 140$ K and sweeping-down current for $T > 80$ K are attributed to the phonon-assisted tunnelling current rather than thermal emission over the barrier (in this case of thermal emission, the lowest barrier is $\Delta E_F = 160$ meV [9]) because the experimentally obtained slope with $1/T$ is only 162 K$^{-1}$, as indicated in the inset of figure 2. The slope is far smaller than the calculated value for thermal emission (1520 K$^{-1}$), but much closer to the value of $\hbar\omega_k/T (=418$ K$^{-1}$) considering that the phonon-assisted tunnelling current is proportional to the averaged number of phonons, i.e. $J \propto (\exp(\hbar\omega_k/kBT) - 1)^{-1}$. Because the averaged number of phonons is limited for the case of $T < 80$ K, the sweeping-down current in the temperature range will not apparently change. The different behaviours for sweeping-up and down currents with temperature clearly indicate that the current for sweeping up ($T < 140$ K) could be described in terms of equation (1) and the currents for sweeping down and up ($T > 140$ K) are determined by different mechanisms of phonon-assistant tunnelling.

It is noted in figure 1 that both the length of the plateau region and the amplitude of hysteresis [12] caused by the spatial charge saving effect in the $I$–$V$ characteristics decrease with increasing temperature. The length of the plateau region in the $I$–$V$ characteristic is $\Delta FN\ell$, where $\Delta F = F_u - F_d$ is the difference in the field strengths between high- and low-field domains. The value of $F_u - F_d$ is marked by the two
measured current versus time at 180 K and 2.8 V.

For doped, weakly coupled SLs, transport properties in the growth direction are described by the following equations: the dimensionless electric field strength corresponding to a real voltage of 2.8 V.

In order to clarify the experimental results, the discrete drift model of electric field domains in the SL is used [10, 11]. In the simulation process, the initial value of $F_i$ is raised to 170 K. In this case, the stable domain boundary becomes a broadened peak. In this case, the electric field has further increase of the valley current, i.e. when $T > 170$ K. When the temperature increases again, for example to $T = 200$ K, the oscillation disappears and the current plateau becomes a broadened peak. In this case, the electric field has basically an averaged distribution over the whole SL.

4. Simulations

In order to clarify the experimental results, the discrete drift model of electric field domains in the SL is used [10, 11]. The electron drift velocity curve $V(F)$ in the equation (2) is derived from the $I-V$ curves measured under different temperatures. In fact, the real drift velocity curve $V(F)$ can be measured only from SLs with very low doping concentration, and cannot be directly obtained from our doped samples. However, from the AB and CD parts of the $I-V$ curves in figure 1, for example, the lineshape of the drift velocity curve can be well depicted because the rising parts of the $I-V$ curves between two neighbouring plateaus are measured in the condition when the high-field domain has been uniformly extended to the whole SL. It is therefore reasonable to derive the $V(F)$ curve from AB and CD parts by assuming that the $V(F)$ curve is composed of two Lorentzian lineshapes of the resonant peaks for the sequential tunnelling current between the subbands. The obtained dimensionless electron drift velocity versus field strength curves for $T = 12, 180$ and 200 K are shown in the inset of figure 4(a). They clearly demonstrate different peak-valley ratios in the lineshape of these curves. The normalized unit field strength corresponds to the field value $F_{\text{max}}$ at the peak point of the $V(F)$ curve. In the simulation process, the initial value of $F (=1.12)$, as indicated by open circles, corresponds to a real voltage of 2.8 V.
and $N_d$ is selected as $2 \times 10^{17}$ cm$^{-3}$, period number $N = 40$, boundary condition $\delta = 10^{-3} \nu \left( \nu = e N_d / (\epsilon F_{12}) \right)$ and $F_{12}$ is the resonant field strength between the ground state and the first excited state in the neighbouring wells). The calculated current versus time curves and the electric field distribution in the SL region are shown in figures 4(a) and (b) for 12, 180 and 200 K respectively. It is noted that the domain boundaries are formed at $T = 12$ K. As $T$ reaches 180 K, however, temporal current oscillations are developed, and the field distribution at the domain boundary is not as sharp as compared to the case of $T = 12$ K. Instead, the domain boundary extends to several quantum wells, as shown by the curve for $T = 180$ K in figure 4(b). As the valley current is further increased with increasing temperature, the current oscillation disappears and the electric field is basically averaged distributed in the SL region, which is shown in the case of 200 K. Therefore, the simulated results can well describe the observed three regimes of the tunnelling processes of field domains. This demonstrates that the properties of domain boundary are critically influenced by the peak–valley ratio in the NDC region of the $V(F)$ curve. It is understood that the domain boundary in the doped SL having a high enough carrier density, as in our sample, will not definitely be in the stable regime. A model including both the carrier density and the $V(F)$ curve should be used to explain the transition from the stable to the dynamic regime in GaAs/AlAs SLs.

5. Conclusions

In conclusion, the experimental results show that both the hysteresis effect in $I$–$V$ curves and the properties of the domain boundary are influenced by the lineshape of the $V(F)$ curve, especially the peak–valley difference of the NDV region. Only when the $I$–$V$ curves overlap each other for both sweeping directions can the transition from a stable to a dynamic domain boundary take place. A further small increase of the valley current may cause temporal current self-oscillations in the SL. The simulated calculation gives a good agreement with the observed results experimentally.

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References