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Experimental observation of spontaneous chaotic current oscillations in GaAs/$Al_{0.45}Ga_{0.55}As$ superlattices at room temperature

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Spontaneous self-sustained chaotic current oscillations are observed experimentally in lightly-doped weakly-coupled GaAs/$Al_{0.45}Ga_{0.55}As$ superlattices at room temperature for the first time. The mole fraction of Aluminum in the barrier is chosen to be 0.45 to suppress the thermal carrier leakage through the X-band valley. The effective nonlinearity induced by the sequential well-to-well resonant tunneling can still be strong enough to induce spontaneous chaotic current oscillations even at room temperature. The frequency spectrum of the chaotic current oscillations is ranged from DC to 4 GHz, which can be used as ultra-wide-band noise sources with a bandwidth of several Giga Hertz.

chaos, superlattice, room temperature

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The study of semiconductor superlattices (SLs), one of the typical low dimensional structures, has formed a major branch of solid-state physics [1]. In 1970, Esaki and Tsu proposed the concept of superlattices that the bulky Brillouin zone can be folded by several tens of time through superlattice effects [2]. Electrons in the center of the shrunk Brillouin zone could be easily drifted into the boundary that negative differential conductance (NDC) could be resulted from, which was expected to used as microwave oscillation resources with a frequency much larger than that of Gunn diodes. However, there are almost no practical applications yet even though the periodic self-sustained current oscillations were be realized in SLs [3,4], since the oscillation frequency cannot achieved to be large as expected and the overall performance was not comparable with GaAs- or InP-based HEMT devices.

Another kind of NDC effect was observed experimentally in weakly-coupled SLs induced by well-to-well sequential resonant tunneling [5]. A lightly-doped weak-coupled SL represent as an ideal one-dimensional nonlinear dynamical system with many degrees of freedom, and the effective nonlinearity is originated from NDC. Indeed, there were a diversify of spatio-temporal patterns observed in DC biased SLs, such as static high-field domains, self-sustained periodic current oscillations, quasi-periodic current oscillations and spontaneous chaotic current oscillations, etc. These spatio-temporal patterns can be observed only below liquid-nitrogen temperature range except that the periodic current oscillations with a frequency range of several GHz were realized at room temperature [6,7].

The occurrence of chaos in a dynamical system relies on much more nonlinearity than that of periodicity. The increase of temperature would reduce the nonlinearity in weakly-coupled SLs. The nonlinearity in SLs is characterized by NDC resulted from the well-to-well sequential resonant tunneling. There are two mechanisms that are responsible for the degradation of the nonlinearity induced by the increasing temperature. As the temperature is increased, the resonant tunneling process would be disturbed by the en-

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hanced phonon scattering and the resonance peak would be lowered and broadened, and thus the peak current would be reduced. Another mechanism is that the increased temperature can activate more carriers thermally in the quantum wells to surpass the barriers to increase the background leakage current. Therefore, the NDC in SLs would be reduced with increasing temperature, since the peak-to-valley ration of the resonant tunneling would be decreased.

The increased background current plays much more important role to the degradation of the nonlinearity induced by increasing temperature, since the thermally activated background leakage current increases exponentially with temperature following the relationship $I_{leakage} \propto \exp(-\Delta E/kT)$, where ΔE is the effective barrier height. In order to get the largest barrier height, GaAs/AlAs SLs are popularly used to eliminate the negative impact on the sequential resonance of the temperate. However, AlAs is an indirect bandgap material, and the X energy valley of AlAs barrier is lower than the Γ energy valley and above to the Γ energy valley of GaAs well by around 100 meV typically [8]. The electrons in the Γ energy valley of GaAs well would be much more easily thermally-excited to the adjacent wells via the X energy valley of AlAs barrier due to the enhance Γ-X mixing induced by the quantum confinement of GaAs/AlAs quantum wells [9–11]. This is the main reason why the nonlinearity of GaAs/AlAs sequential resonant tunneling cannot meet the requirement of the occurrence of chaos at room temperature.

In this paper, lightly-doped weak-coupled GaAs/$Al_{0.45}Ga_{0.55}As$ SLs are used to replace GaAs/AlAs SLs to investigate the nonlinear dynamic behavior. The $Al_{0.45}Ga_{0.55}As$ barrier layer is direct bandgap material where the energy of X valley is very close to that of Γ valley. The lowest energy level of $Al_{0.45}Ga_{0.55}As$ barrier is 390 meV higher than that of GaAs wells so that the thermal-excited process of electrons in GaAs quantum wells can be effectively quenched. This can provide the strong nonlinearity enough to stimulate the chaos in GaAs/$Al_{0.45}Ga_{0.55}As$ SLs. Indeed, spontaneous self-sustained chaotic current oscillations are, for the first time, observed experimentally in GaAs/$Al_{0.45}Ga_{0.55}As$ SLs at room temperature. The frequency spectrum of chaotic current oscillations is so large that it can be used as wide-band noise sources with a bandwidth of GHz.

The investigated samples consist of 50-period, weakly-coupled GaAs/$Al_{0.45}Ga_{0.55}As$ superlattice with 7.0-nm GaAs wells and 4.0-nm $Al_{0.45}Ga_{0.55}As$ barriers. The width of lowest conduction miniband is calculated to be 2 meV, therefore the SLs are weakly coupled. Each GaAs quantum well is doped by Si with 3.0×10^{17} cm^{-3} within the central of 3.0 nm, and there is a spacing of 2.0 nm to GaAs/$Al_{0.45}Ga_{0.55}As$ interface to avoid the diffusion of Si atoms into $Al_{0.45}Ga_{0.55}As$ barriers. The GaAs/$Al_{0.45}Ga_{0.55}As$ superlattice is sandwiched within two 300-nm GaAs contacting layers with Si doping of 5.0×10^{18} cm^{-3} to form n^+-n-n^+ diode structure. AuGe/Ni Ohmic contact is alloyed on the top and on the substrate side. The devices are mesa-etched with a diameter of 150 μm, and then are mounted into the packages using high-frequency coaxial cable with a bandwidth of 20 GHz. The current oscillations are detected and recorded with a digital oscilloscope with a sampling rate of 20 Gbit/s and a spectrum analyzer. All experimental data are collected at room temperature.

As GaAs/$Al_{0.45}Ga_{0.55}As$ SLs are biased at the DC voltage range from 6.21 to 6.80 V, chaotic current oscillations are observed. Figure 1 shows a frequency spectrum of such a typical chaotic oscillation of the SL biased at 6.50 V. This spectrum is ultra-wide and very noisy with a frequency distribution ranging from DC to 4 GHz, which provides the clear signatures of spontaneous chaos that was previously demonstrated experimentally in GaAs/AlAs SLs under liquid-helium temperature [12]. To the best knowledge we know, there has been no report so far on the experimental observation of spontaneous chaos in semiconductor SLs at room temperature, and this means that it is highly promising for SLs to have practical applications, such as true random number generators (RNGs).

It should be pointed that the spontaneous chaos in GaAs/AlAs SLs was disappeared and only periodic current oscillations still were observed as the temperature is increased to about 60 K [13]. As we know, the occurrence of spontaneous chaos relies on much stronger than that of the periodicities. The experimental results of Figure 1 demonstrate that the strong nonlinearity of GaAs/$Al_{0.45}Ga_{0.55}As$ SLs can be maintained at room temperature superior to GaAs/AlAs SLs. The main reason is that GaAs/$Al_{0.45}Ga_{0.55}As$ SLs can efficiently quench the thermal excited background current than GaAs/AlAs SLs, which can be understood clearly with the aid of conduction-band diagram of GaAs/$Al_{0.45}Ga_{0.55}As$ SLs and GaAs/AlAs SLs.

Figure 2(a) and (b) show the conduction-band diagram of GaAs/AlAs and GaAs/$Al_{0.45}Ga_{0.55}As$ SLs, respectively. Both SL structures are with 7.0-nm quantum well and 4.0-nm barrier. The calculated energy levels of Γ valley quantum confined states in GaAs quantum wells relative to the

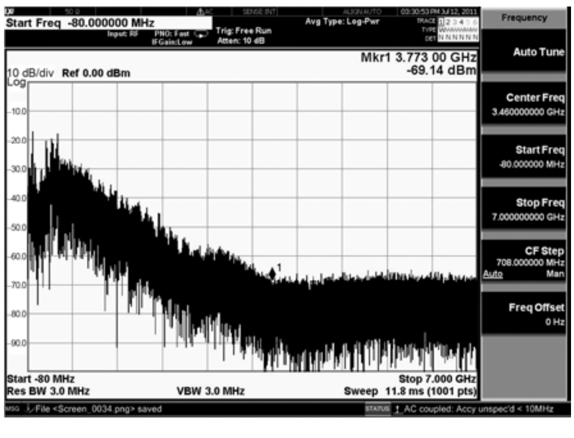

Figure 1 Frequency spectrum of the spontaneous chaotic oscillation of GaAs/$Al_{0.45}Ga_{0.55}As$ superlattices with a DC bias voltage of 6.50 V.

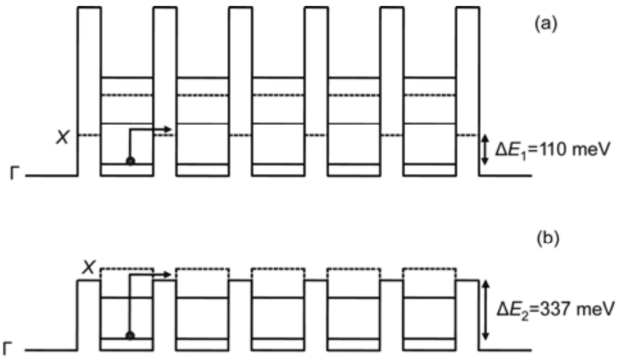

Figure 2 Conduction-band diagram of (a) GaAs/AlAs SLs and (b) GaAs/$Al_{0.45}Ga_{0.55}As$ SLs.

minimum of Γ valley of GaAs are 65, 257 meV for GaAs/AlAs structure and 53, 207 meV for GaAs/$Al_{0.45}Ga_{0.55}As$ SL structure, respectively. The minimum of X valley of AlAs layer is 160 meV above to the minimum of Γ valley of GaAs even the quantum confinement of AlAs was taken into account [11]. There is a barrier height (ΔE_1) of (160–65+15)=110 meV for the thermally excited electrons from the ground state of GaAs quantum wells to surpass the AlAs barriers through Γ-X transfer. The minimum of Γ and X valleys of $Al_{0.45}Ga_{0.55}As$ are very close, about 390 meV above to Γ valley of GaAs [14]. The barrier height for thermally-excited electrons in quantum wells to surpass the $Al_{0.45}Ga_{0.55}As$ barriers (ΔE_2) is (390–53)=337 meV, which is 227 meV larger than ΔE_1. Consequently, the thermal-induced background current of GaAs/$Al_{0.45}Ga_{0.55}As$ SLs is about $\exp[-(\Delta E_2-\Delta E_1)]=1.6\times10^{-4}$ times that of GaAs/AlAs SLs at room temperature. Thus the thermally-excited electrons can be effectively reduced, resulting in spontaneous chaotic oscillation at room temperature.

In conclusion, spontaneous chaotic current oscillations with a bandwidth of GHz have been experimentally demonstrated in light-doped, weakly-coupled GaAs/$Al_{0.45}Ga_{0.55}As$ SLs at room temperature, while similar phenomena can be observed only at liquid-helium temperature ever before. The employment of GaAs/$Al_{0.45}Ga_{0.55}As$ SLs can eliminate the leakage current induced by thermally excited Γ-X intervalley transfer more effectively than GaAs/AlAs SLs, and the nonlinearity of GaAs/$Al_{0.45}Ga_{0.55}As$ SLs is strong enough to stimulate spontaneous chaos even at room temperature. The SL n^+-n-n^+ diodes with a function of spontaneous chaotic current oscillation, which can operate under room temperature environment, can be eligibly applied in fast physical RNGs.

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