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Time Constant for High-Field Domain Formation in Multiple Quantum Well Sequential Resonant Tunneling Diodes

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We have investigated the frequency dependence of the tunneling current-voltage (*I-V*) characteristics of $GaAs/Al_{0.3}Ga_{0.7}As$ multiple quantum well (MQW) sequential resonant tunneling diodes. Although clear periodic negative differential resistances (NDRs) are observed in the dc measurement, such NDRs are found to disappear at high frequencies, indicating a finite time constant necessary for the formation of stable high-field domains. The observed time constant has been well explained by the product of the capacitance of a tunneling barrier and the intrinsic tunneling resistance in the low-field domain.

1. Introduction

Quantum transport in doped MQWs has attracted much attention due to its application to novel THz photodetectors and emitters.[1-3] It is well known that the *I-V* characteristics due to sequential resonant tunneling through the active regions of such MQWs show plateau-like regions, each of which exhibits periodic negative differential resistances with rather constant peak and valley current. Such a behavior has been explained by the formation of high-field domain and sequential resonant tunneling through them.[4-8] Recently, the importance of the dynamics of the domain formation is recognized and the investigation along this line has been started.[9]

In this work, we have investigated the frequency dependence of the tunneling *I-V* characteristics of $GaAs/Al_{0.3}Ga_{0.7}As$ MQW sequential resonant tunneling diodes. Although clear periodic NDRs are observed in the dc measurement, such NDRs are found to disappear at high frequencies, indicating a finite time constant necessary for the formation of stable high-field domains. The observed time constant has been well explained by the product of the capacitance of a tunneling barrier and the tunneling resistance in the low-field domain.

2. Experimental

The $GaAs/Al_{0.3}Ga_{0.7}As$ MQW structure investigated in this work was grown on an n^+-GaAs substrate by molecular beam epitaxy (MBE). The active layer of the samples consisted of 20 periods of 250 Å-wide GaAs quantum wells and 100 Å-thick AlGaAs barriers. The samples were uniformly doped with Si up to 5×10^{15} cm^{-3} in the whole active MQW region. The substrate temperature during MBE growth of the active regions was kept at 530 °C to suppress the dopant segregation. The MQW active regions were sandwiched between 0.5 μm-thick n^+-GaAs capping and buffer layers. The samples were etched into mesa shapes of 400 × 400 μm^2 defined by standard photolithography. Tunneling *I-V* characteristics were measured between the top and bottom ohmic electrodes at 4.2 K. The dc *I-V* characteristics were measured by using a semiconductor parameter analyzer. The time dependent tunneling current was measured by using a digital oscilloscope and an output of a function generator.

3. Frequency dependence of the domain formation

Figure 1 show the dc *I-V* characteristics of the MQW structures investigated in this work (Fig 1(a)), and the blowup of the *I-V* characteristics in the first plateau (Fig. 2(b)). As shown in Fig. 1(a), the *I-V* characteristics consist of plateau-like regions, in each of which periodic NDRs with rather constant peak and valley current are observed. The electron transport mechanism through such a MQW structure has been attributed to the resonant tunneling process between the two dimensional (2D) subbands in the neighboring quantum wells. The plateaus in the *I-V* characteristics are formed as the high-field domains grow with an external bias. The voltage differences between the successive NDRs in each plateau are approximately equal with the energy differences between the 2D subbands in quantum well.

Figure 2 shows the *I-V* characteristics of the MQW diodes measured by using triangular voltage sweeps at various frequencies f. As shown in the Fig. 2, clear periodic NDRs due to high-field domain formation are observed up to 1 kHz. However, the amplitude of the NDRs becomes smaller as f is further increased, and eventually they disappear at about f = 50 kHz. This fact clearly indicates a finite time constant necessary for high-field domain formation. In order for static domains to be formed, non-equilibrium charge accumulation at the domain boundary is necessary to support the difference in

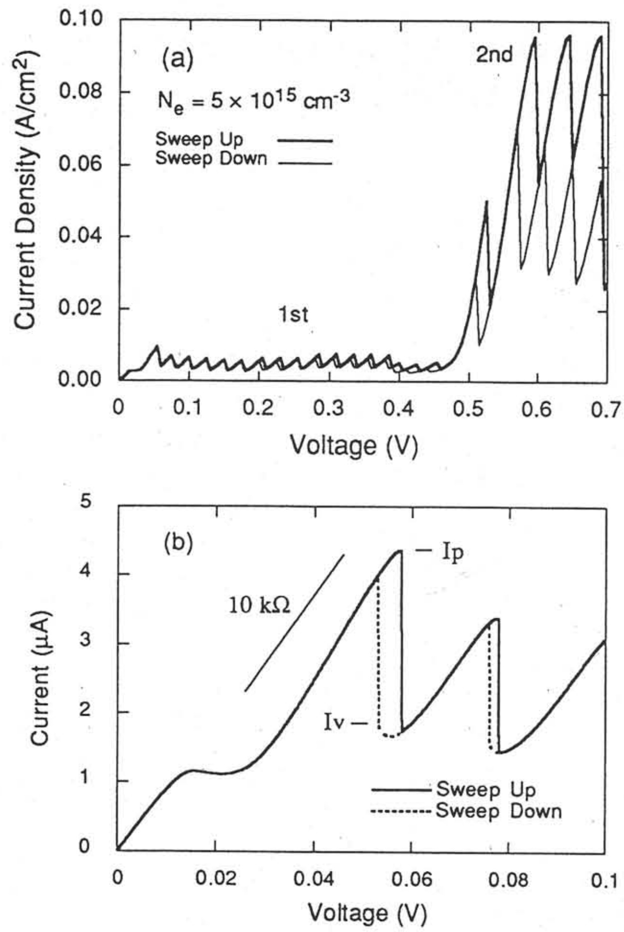

Fig. 1 (a) The dc *I-V* characteristics of a uniformly-doped $GaAs/Al_{0.3}Ga_{0.7}As$ MQW diodes, and (b) the blowup of the I-V characteristics in the first plateau.

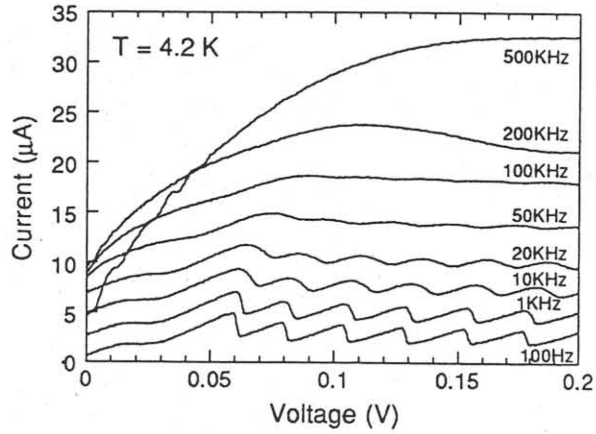

Fig. 2 The *I-V* characteristics of the MQW diodes measured by using triangular voltage sweeps at various frequencies.

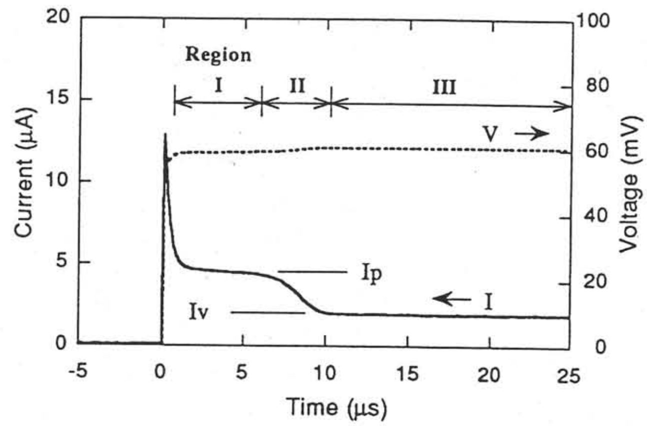

Fig. 3 The temporal response of the tunneling current (solid line) to a stepped applied voltage (dotted line).

electric field between in the high- and low-field domains. Such charges must be supplied through a series resistance R_S of the structure to the tunnel barrier capacitance C_T at the domain boundary. The R_S was determined to be about 10 kΩ from the differential conductance of the measured quasi-static *I-V* characteristics shown in Fig. 1(b). From a theoretical calculation of the tunneling current based on a density matrix approach,[10,11] we have found that the dominant R_S in the MQW structure is not due to an extrinsic factor such as contact resistances but due to the tunneling resistance in the low-field domain. The tunnel barrier capacitance C_T was calculated to be about 500 pF from the geometry. By multiplying R_S and C_T, the cutoff frequency f_{CR} was obtained to be about 30 kHz ($\tau_{CR} \sim 5$ μs), which is in good agreement with the experimental result.

4. Temporal response of the tunneling current

In order to observe the dynamical effect more directly, we have investigated the temporal response of the *I-V* characteristics to the stepped applied voltage (Fig. 3). The stepped voltage of about 60 mV was applied to the diode in order to set the steady state *I-V* characteristics in the first valley region. The very initial current spike is a displacement current through the tunneling capacitance. The first, rather constant current denoted as region I is equal to the resonant peak current, while the steady current in region III is equal to the nonresonant valley current (Fig. 1(b)). Between the regions I and III, a clear transient from the resonant state to the nonresonant state is observed (region II). The observed 5 μs-long transient corresponds to the time necessary for accumulating charges at the domain boundary and is in excellent agreement with τ_{CR} estimated above.

5. Conclusion

In conclusion, we have investigated the frequency and temporal dependence of the tunneling *I-V* characteristics of GaAs/$Al_{0.3}Ga_{0.7}As$ MQW sequential resonant tunneling diodes. The *I-V* characteristics show a remarkable frequency dependence; i.e., the formation of high-field domains is not able to follow the high frequency applied electric fields. Furthermore, the temporal response of the tunneling current to a stepped voltage clearly exhibits a finite transient from the peak to valley current. It is found that such a finite time constant necessary to form high-field domains is well explained by the product of the capacitance of a tunneling barrier and the intrinsic tunneling resistance in the low-field domain.

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