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Doping Effects on the Resonant Tunneling Characteristics of InGaAs/InAlAs MQW Diodes

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Clear negative differential resistance (NDR) and oscillatory conductance are observed at room temperature in a wide voltage region for the InGaAs/InAlAs MQW diode with Si-doped well structure. The NDR peak current of undoped well structures decreases with increasing temperature, while that of Si-doed well structures increases with temperature. The oscillation period was found to decrease with increasing temperature for both structure.

I. Introductions

Multiple quantum well (MQW) structures exhibit unique transport properties related to quantum effects, such as oscillatory conductance[1-4], and effective mass filtering effects[5]. We have already reported an observation of clear negative differential resistance (NDR) followed by oscillatory conductance in forward current voltage (I-V) characteristics of InGaAs/InAlAs MQW diodes at 77K[3,6]. In contrast to conventional double barrier (DB) diode structures, the NDR region of the InGaAs/InAlAs MQW diodes can be controlled by changing the MQW well numbers, and a wide NDR region is possible. Using the NDR, a new type of bistable MQW laser was proposed and demonstrated.[7]

In this paper, Si-doping effects on the resonant tunneling character--istics are studied. A clear NDR is observed at room temperature in the InGaAs/InAlAs MQW diodes with Si-doped wells. Temperature dependence of the NDR characteristic of the MQW diodes with undoped well structures and Si-doped well structures is also studied.

II. Effects of Si-doping on Resonant tunneling characteristics

Figure 1 shows the structure of the InGaAs/InAlAs MQW diodes studied. This structure is grown on S-doped

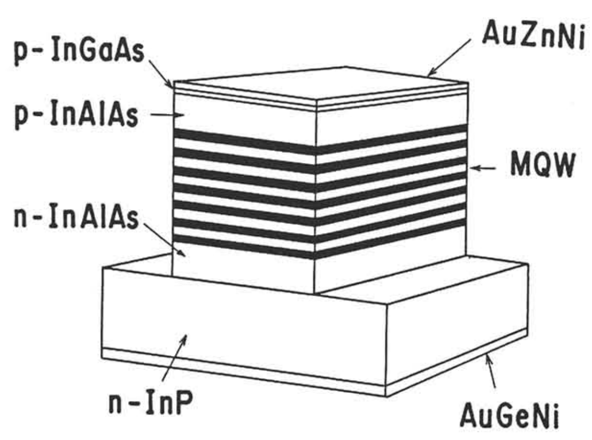

Fig.1 Structure of the InGaAs/InAlAs MQW diode

(100) InP substrates by molecular beam epitaxy. It consists of a Si-doped lower InAlAs cladding layer($n=1x10^{18}$ cm^{-3}.), an InGaAs/InAlAs MQW layer(40 wells or 10 wells), a Be-doped upper InAlAs cladding layer($p=1x10^{18}$ cm^{-3}), and a Be-doped InGaAs cap layer($p=2x10^{18}$). The InGaAs well width and InAlAs barrier width are both 67Å. The InGaAs well layers are Si-doped ($1x10^{18}$ cm^{-3}). For comparison, MQW diodes with undoped InGaAs well layers are also grown. The MQW wafers were fabricated into diode chips with a 100 μm mesa width and 200 μm lengths.

Figure 2 shows the room temperature forward I-V characteristics for the MQW diode with (a) Si-doped wells (40 wells) and (b) undoped wells (40 wells). The NDR and oscillatory behavior can be clearly observed for the MQW diodes with Si-doped wells. In contrast, in the case of MQW diodes with undoped wells, the NDR almost disappears at 300K. This is because of the decrease in the peak current with increasing temperature, as shown later. The results shown in Fig.2 suggests that Si-doping into InGaAs wells plays an important role in observing clear NDR at room temperature in Si-doped well structures.

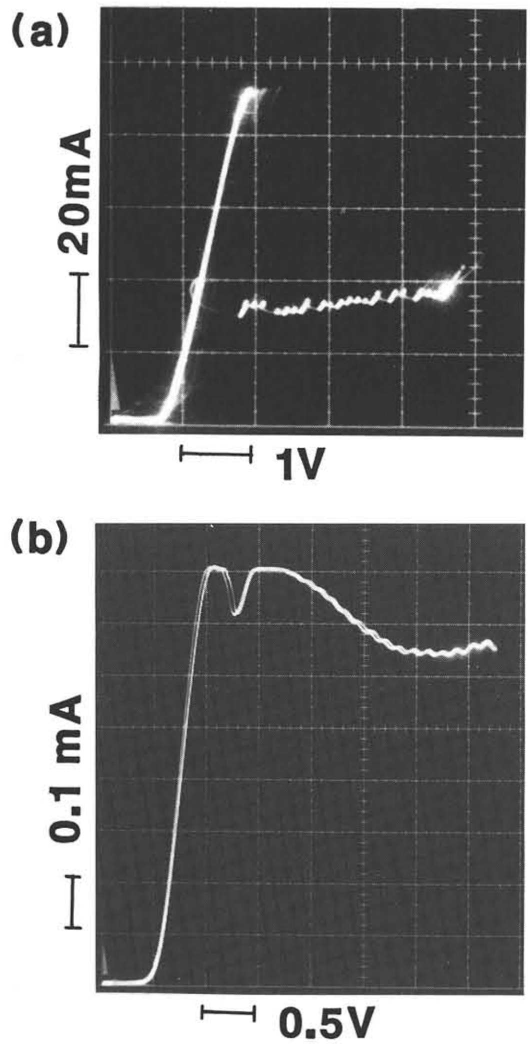

Fig.2 I-V characteristics of InGaAs/ InAlAs MQW diodes.

III. Temperature dependence of the resonant tunneling characteristics.

The experiments were carried out from 4k to 300K for both undoped and Si-doped MQW diodes. Figure 3 shows the temperature dependence of the peak current for the MQW diode with undoped wells (10 and 40 wells). As shown in the figure, the peak currents of the NDR for both samples remains constant at low temperature and then starts to decrease sharply with an increase in temperature. In paticular, the decrease in the peak current of the MQW diode with 40 wells occurs at lower temperatures than that for 10 wells.

The decrease in the peak current observed here is considered to be caused mainly by the decrease in the phonon scattering length in the MQW layer. When the phonon scattering length becomes shorter than the MQW thickness, the scattering effect in

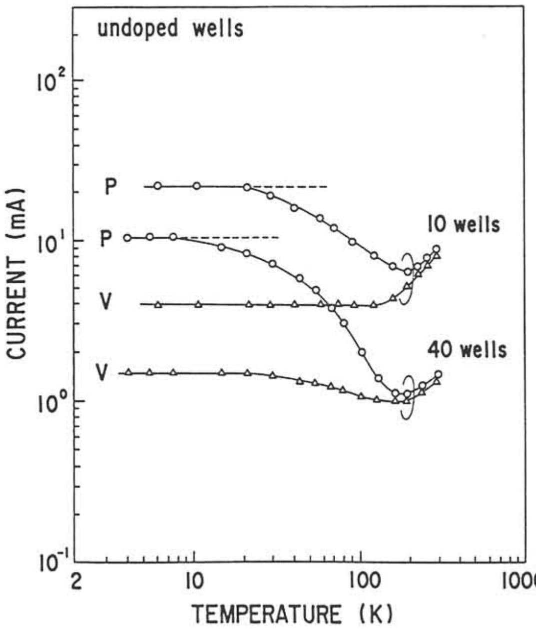

Fig.3 Temperature dependence of the NDR for undoped well structures

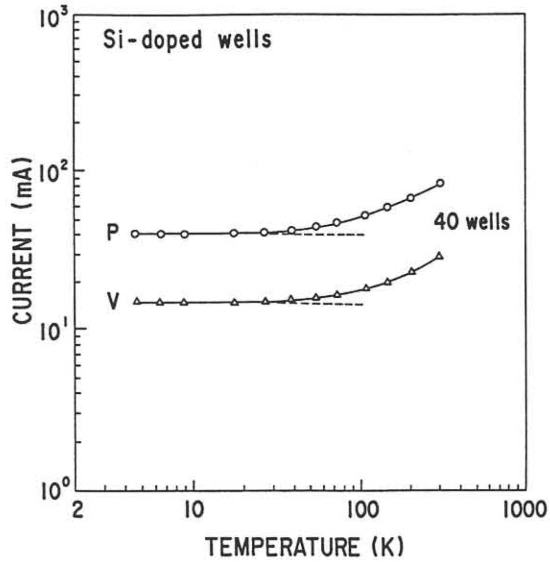

Fig.4 Temperature dependence of the NDR for Si-doped well structures

the MQW layers becomes dominant, which reduces the peak value of the transmission probability at resonance.[5,8,9] This leads to a decrease in the tunneling current when the energy distribution of the incoming electrons is narrow compared with the resonance width[10]. This model explains the difference between the MQW diodes with 10 wells and 40 wells. However, further studies are necessary to clear the mechanism of the temperature dependence of the valley current.

The temperature dependence of the MQW diodes with Si-doped wells having 40 wells is shown in Fig.4. In contrast to the case for undoped well structures, the peak current of the MQW diode with Si-doped wells remains constant below 40K and gradually increases with increasing temperature. It should be noted that the peak/valley ratio is almost constant in all temperature ranges.

The difference in the temperature dependences between Si-doped well structures and undoped well structures is considered to be as follows. In the case of Si-doped well structures, high density electrons exsist in each well. Therefore, the tunneling current through the MQW layer can be observed when electrons in each well transfer from the wells to adjacent wells by the resonant tunneling. In other words, tunneling through one barrier is enough to induce the tunneling current. In this case, the effect of phonon scattering is small, although the scattering length in the Si-doped well structure will be shorter than that in the undoped well structure.

Figure 5 shows the temperature dependence of the oscillation period $\Delta E(osc)$ for both undoped and Si-doped well structures. For comparison, the

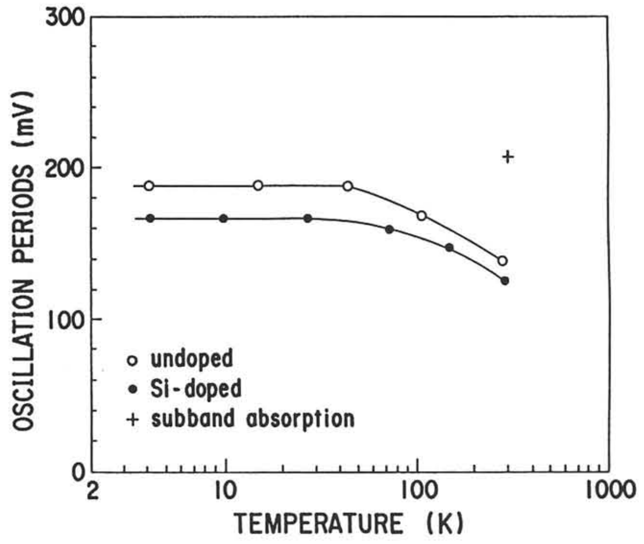

Fig.5 Temperature dependence of the oscillation periods

energy difference ΔE_{21} between the ground subband level and the 1st excited subband levels obtained from room temperature intersubband absorption is shown. It can be seen in this figure that $\Delta E(osc)$ for both undoped and Si-doped well structures gradually decreases above 40K. The reason for the decrease in $\Delta E(osc)$ is not clear at present. One of the possiblities is the decrease in the conduction band discontinuity ΔEc with an increase in temperature. Another possibility is the decrease in life time in the excited subband level, which causes the decrease in $\Delta E(osc)$.[2] However, the difference between $\Delta E(osc)$ and ΔE_{21} at room temperature is more than 50 meV, which is too large to be explained only by the scattering life time in the subband levels. It seems that some other reasons are responsible for this energy difference between $\Delta E(osc)$ and ΔE_{21}.

III. Summary

Clear NDR is observed at room temperature in InGaAs/InAlAs MQW diodes with Si-doped well structures in a wide voltage region. It becomes clear that the peak current of undoped well structures decreases with increasing temperature, while that of Si-doped well structures increases with temperature. Also, the oscillation period was found to decrease with increasing temperature for both structures.

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