第26卷第2期
2007年4月

红外与毫米波学报
J. Infrared Millim. Waves

Vol. 26, No. 2
April, 2007

文章编号:1001-9014(2007)02-0081-04

GREATLY ENHANCED RESONANT TUNNELING OF PHOTO-EXCITED HOLES IN A THREE-BARRIER RESONANT TUNNELING STRUCTURE

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Abstract: By integrating a resonant tunneling diode with a 1.2μm-thick slightly doped n-type GaAs layer in a three-barrier, two-well resonant tunneling structure, the resonant tunneling of photo-excited holes exhibits a value of peak-to-valley current ratio (PVCR) as high as 36. A vast number of photo-excited holes generated in this 1.2μm-thick slightly doped n-type GaAs layer, and the quantization of hole levels in a 23nm-thick quantum well on the outgoing side of hole tunneling out off the resonant tunneling diode which greatly depressed the valley current of the holes, are thought to be responsible for such greatly enhanced PVCR.

Key words: photo-excitation; holes; resonant tunneling; peak-to-valley current ratio (PVCR)
CLC number: 047 **Document**: A

三势垒共振隧穿结构中极大增强的光生空穴共振隧穿

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摘要:研究了电子隧穿出射端嵌入1.2μm厚n型弱掺杂GaAs层的三势垒双阱隧穿结构,观察到了隧穿峰谷比高达36的光生空穴共振隧穿峰.研究证实1.2μm厚n型弱掺杂GaAs层在光照下产生的大量光生空穴以及空穴隧穿出射端的23nm宽的量子阱中量子化的空穴能级对空穴隧穿谷电流的限制作用,是导致高峰谷比的光生空穴隧穿现象的主要原因.

关 键 词:光激发;空穴;共振隧穿;峰谷比

Introduction

Resonant tunneling diodes (RTDs) have been extensively investigated in the last three decades inspired by their potential use in high-speed electronics and multi-valued logic devices. While the characteristic peak-to-valley current ratio (PVCR) in n-type GaAs/AlAs and InP-based AlInAsSb/InGaAs RTDs already reach very high values over 12 and 46 respectively even at the room temperature [1,2], p-type GaAs/AlAs RTD only reveals PVCR close to 4 at 15K [3~5] due to a considerable mixing between light-hole (LH) and heavy-hole (HH) states. On the other hand, although, the roles of photo-excited holes in n-type RTD structures has been addressed previously in the context of photoluminescence (PL) behaviors of RTDs[6], and very re-

Received date: 2006-11-27, **revised date**: 2006-12-29 **收稿日期**:2005-11-27, **修回日期**:2006-12-29
Foudantion item: Supported by the Major State Basic Research Project of China (Gool CB3095)
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cently has been employed as a scheme for single photon detection[7]. However, an excellent hole-resonant-tunneling characteristic with a reasonably high PVCR has been seldom reported.

In this paper we report on the greatly enhanced resonant tunneling of photo-excited holes in n-i-n triple-barrier resonant tunneling structures. By deliberately extending the thickness of a weakly doped n-type GaAs buffer layer to 1.2μm on the collector side of RTD, a PVCR of 36 has been reached for the hole-resonant tunneling under low illumination intensity at 15K.

1 Experiment

For experiments, specially designed heterostructures have been grown by molecular beam epitaxy (MBE). A 500 nm-thick n^+-GaAs buffer layer, Si-doped to $1.0\times10^{18}cm^{-3}$, was first grown on n^+-type (100) GaAs substrate, and then followed by a 1.2μm-thick GaAs layer, Si-doped to $1.0\times10^{15}cm^{-3}$ (sample 1) or a 20 nm-thick undoped GaAs layer (sample 2). The undoped three-barrier, two-well structure was constructed in growth sequence by a 2.5nm-thick AlAs barrier, a 7.5nm-thick GaAs well (central QW), a 5.0nm-thick AlAs barrier, a 23nm-thick GaAs well (incident QW), a 5.0 nm-thick $Al_{0.4}Ga_{0.6}As$ barrier, and a triangle-like $Al_xGa_{1-x}As$ barrier with the mole fraction x graded from 0.4 to 0.2 over a thickness of 35nm. The top contact layer consisted of a 100 nm-thick $n^+-Al_{0.2}Ga_{0.8}As$ layer, Si-doped to 1×10^{18} cm^{-3}, a 100 nm-thick $n^+-Al_{0.2}Ga_{0.8}As$ layer, Si-doped to 4×10^{18} cm^{-3}, and a 50 nm-thick n^+-GaAs cap layer, Si-doped to $4.0\times10^{18}cm^{-3}$. The sample was processed by standard photolithography techniques into rectangular mesa ($650\times350μm^2$), and n-type ohmic contacts were separately applied to the top and back contact-layers. By evaporating and subsequently alloying a rectangular Au/Ge/Ni contact pattern onto the cap layer, the top contact was formed with a square aperture ($200\times200μm^2$) left for the optical access. The back contact was made by evaporating and alloying Au/Ge/Ni to the n^+-type GaAs substrate.

For the measurement, the sample was mounted on the cold finger of a variable-temperature closed-cycle helium cryostat and cooled to ~15 K. A cw-Ti:sapphire laser with the wavelength tunable between 820 nm and 840 nm was used for photo-excitation. A Hewlett-Packard 4140B pA meter was used to measure the I-V characteristics of the samples.

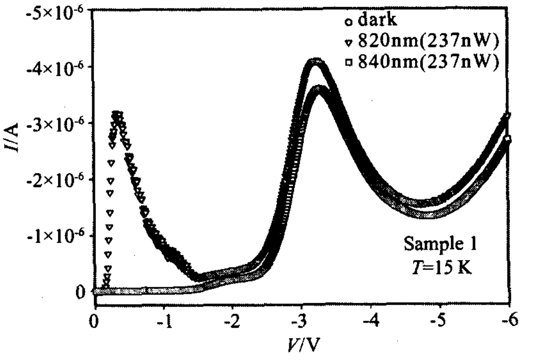

Fig. 1 Current-voltage characteristics measured under dark and the laser irradiations of different two wavelengths of 820 and 840 nm

图1 不同波长的激发光照射下,样品的 *I-V* 特性曲线

2 Results and Discussion

Figure 1 shows the I V characteristics of the sample 1 measured at 15 K under reverse bias (referring to the top contact being negatively biased with respect to the bottom contact). In the absence of laser irradiation, electrons from the top contact layer are allowed to flow over the first triangle barrier into the first well, where electrons first cascade down to lower-lying subbands before they escape out of the incident well by tunneling through the DBS in down-stream direction. The schematic of energy band profile of the structure is depicted in figure 2.

In the dark condition, the main resonant current peak, appearing at about -3.3V in figure 1, is unambiguously assigned to the resonant tunneling between the ground subband (E_1) in incident wide QW and that in the central QW (E'_1) (see figure 2). The weaker current peak on the lower bias side (-1.8V) stems from the resonant tunneling between E_2 and E'_1 subbands due to the partial filling in E_2subband by injection from the emitter. When the sample1 is illuminated by 820nm laser irradiation with its photon energy just larger than the GaAs band gap, a new resonance peak appears at about 0.35V, significantly below the peak positions of the resonant tunneling for both E_1-to-E'_1

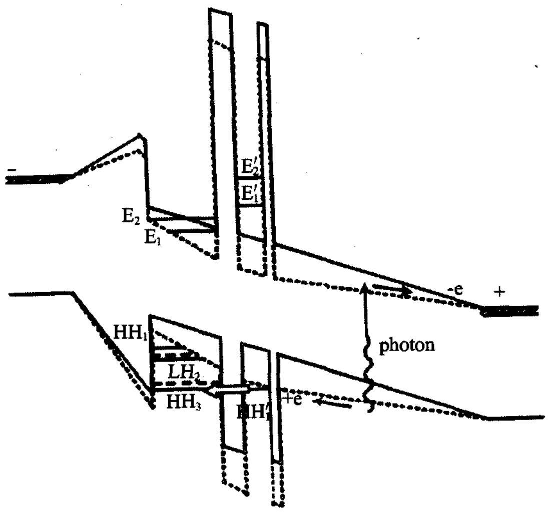

Fig. 2 Schematic of the band-edge profile of the device under reverse bias

图 2 负偏压状态下样品有源区的带边结构示意图

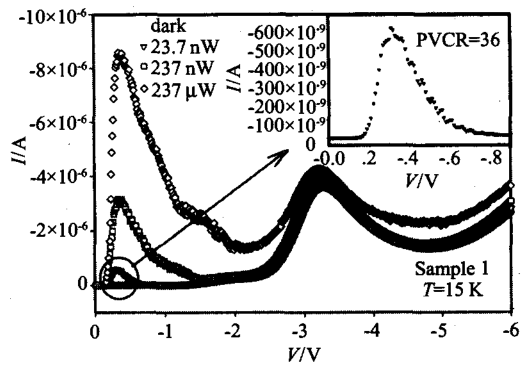

Fig. 3 Current-voltage characteristics measured at reverse biases under the dark and 820nm laser irradiation with different power, the magnified portion in the inset show a PVCR of 36 under 23.7nW illumination

图 3 负偏压状态时,不同激发光功率照射下,样品的 I-V 特性曲线. 在插图中放大显示了在 23.7nW 激发光功率照射下,峰谷比高达 36 的光生空穴共振隧穿峰

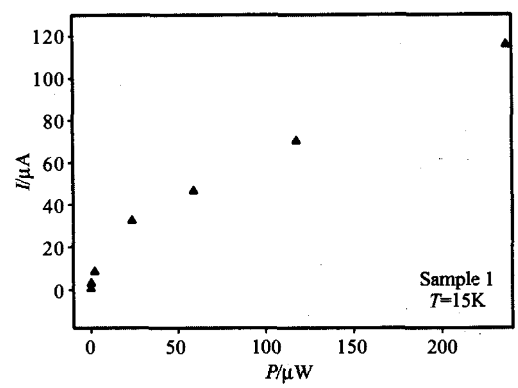

Fig. 4 The dependence of peak hole current on the illumination intensity of 820 nm-laser light

图 4 空穴隧穿峰值电流与 820nm 波长激发光光功率值的关系曲线

and E_2-to-E_1'. However, no such peak shows up under 840nm laser illumination, the photon energy of which is smaller than the GaAs band gap. The *I-V* curve under 840nm laser illumination essentially coincides with that under the dark. This observation clearly indicates that the appearance of the new tunneling peak under 820nm laser irradiation is closely related to the photo-excited holes in 1.2μm-thick GaAs layer and their resonant tunneling through HH'_1 subband in the central well.

To provide further evidence, the *I-V* characteristics of the sample 2, in which a 20nm-thick undoped GaAs layer replaces the 1.2μm-thick GaAs layer on the collector side, have been also measured with and without 820nm laser irradiation (not shown). No discernible difference in the *I-V* characteristics is found in the absence and presence of illumination, since both the photo-generation of the carriers and their modulation on the electrostatic potential profile become negligibly smaller in the case of sample 2 [8,9].

The *I-V* characteristics of the sample 1 have been measured in figure 3 under different illumination intensities (dark and 23.7nW, 237nW, 2.37μW 820nm-laser-irradiations). When the illumination intensities are below 237nW, the peak current of the hole resonant tunneling increases very rapidly with the irradiation power, while the current peak from the electron resonant tunneling remains almost unchanged. That is also in consistence with the picture for the occurrence of the resonant tunneling of photo-excited holes in low bias range. As the illumination intensity is raised above 2.37μW, the valley current between the hole peak and electron peak is increased due to the flooding of accumulated photo-excited holes near the collector barrier over the triangle $Al_xGa_{1-x}As$ barrier as seen in figure 2. Eventually, the hole peak completely dominants over the electron peak with increasing illumination intensity. Figure 4 plots out the dependence of peak hole current on the illumination intensity.

On the other hand, the hole tunneling shows a PVCR of 36 under 23.7nW illumination as seen from the magnified portion in the inset of figure 3. Although, the resonant tunneling of photo-excided holes has been previously reported[9,10]. To the best of our knowledge, a PVCR as high as 36 has not jet been observed for the hole resonant tunneling. Obviously, as an optical absorption medium, the 1.2μm-thick n-type GaAs layer can provide a much large number of photo-excited holes that are swept to the vicinity of the collector as the vast source for hole tunneling. This greatly enhances the peak current of the hole tunneling. Furthermore, the quantization of hole levels in the 23nm-thick GaAs quantum well plays a role of the energy filter that further helps to enhance resonant peak current and depress the valley current, leading to a high PVCR. An estimated hole level-ladder in the 23nm-thick GaAs quantum well is depicted in figure 2. The highest-lying hole subbands, LH_2/HH_3 (LH_2 the second light hole subband, HH_3 the third heavy hole subband), can in deed be taken as such energy filter. Once the energy of holes outgoing from DBR is higher than the top of triangle $Al_xGa_{1-x}As$ barrier, the mentioned energy-filter-effect losses, and the holes start to flood over.

3 Summary

In a three-barrier, two-well n-type resonant tunneling structure integrated with a 1.2μm-thick GaAs absorption layer, the resonant tunneling of photo-excited holes exhibits a PVCR value of 36. Such greatly enhanced PVCR has been attributed to the following two mechanisms: 1. a large number of photo-excited holes generated in this thick absorption layer are swept to the vicinity of the collector, and become a vast hole's source, leading to greatly enhanced peak current of the hole tunneling. 2. the quantization of hole levels in the 23nm-thick GaAs quantum well on the outgoing side of hole tunneling out off RTD plays a role of the energy filter that further helps to enhance resonant peak current and depress the valley current.

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