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STUDY ON SUBSTRATE-LIFTED-OFF QUANTUM WELL INFRARED PHOTODETECTOR

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Abstract: Epitaxial films of GaAs/AlGaAs multi-quantum wells were lifted-off from its grown substrate and transferred to a Si substrate, a typical infrared optical window material. The lifted-off sample was fabricated into quantum well infrared photodetector (QWIP). The responsivity and photocurrent spectrum of the lifted-off QWIP is shown in similar to that of QWIP processed from the as-grown wafer. It demonstrates that the lift-off process can be used in QWIP process without device performance degradation. The lifted-off process can provide a new possibility to integrate the QWIP devices with other optical device to enhance the detector performance.

Key words: substrate lift-off; quantum well infrared detector; photocurrent spectra; dielectric function
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衬底剥离的量子阱红外探测器研究

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摘要:对用MBE生长的GaAs/AlGaAs量子阱材料进行了衬底剥离,在此基础上制备了单元器件并测量了器件的黑体响应率以及光电流响应.实验解决了衬底剥离及器件制备中的工艺问题,研究了衬底剥离对材料及器件性能的影响以及用这种方法制备器件的可行性.结果表明选择腐蚀法是一种有效的衬底剥离方法,用这种方法得到的多量子阱薄膜材料仍具有较好的红外探测性能,为进一步实验提供了依据.

关 键 词:衬底剥离;量子阱红外探测器;光电流谱;介电函数

Introduction

The possibility for using multiple quantum well (MQW) structures to detect infrared radiation was first suggested by Smith[1]. Since then, a lot of work has been done on quantum well infrared photodetector (QWIP) and great progress has been achieved[2-6]. It was shown that the lattice matched GaAs/Al_xGa_{1-x} As material system is a good candidate to construct quantum well (QW) structures. By changing the Al proportion x and the QW width, the intersubband transition energy can be varied from 3 to 18μm. Besides, GaAs based materials and device processing have become a mature technology. This technology facilitates highly uniform, large format QWIP focal plane arrays (FPA) with high yield and reproducibility.

However, the quantum efficiency (QE) of QWIP is much smaller than that of HgCdTe due to very small effective absorption thickness of QWs. It is one of the fundamental difficulties for QWIP. Recently, photonic band gap (PBG) materials attracted a lot of interest and its applications in many aspects have been stud-

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ied[7,8]. The manipulation of the photon can be easily achieved in PBG material. It gives high possibility to improve the QE of QWIP by integration of PBG with QWIP. Then the bonding between the QWIP material with the PBG material is necessary. A convenient way is to use the lift-off QWs film for PBG-QWIP integration. Thus, a non-degrading QWIP using lift-off QWs film is important. Some papers have described a method of epitaxial lift-off (ELO) to make the QWs film[9], but QWIPs made of the lifted-off QWs films have never been reported so far. In this paper we present the results of our study on the substrate lifted-off QWIP.

1 Experiment

The epitaxial film structure in our experiment was grown by MBE on semi-insulating (100) GaAs substrate. It began with 100nm-thick AlAs used as the release layer in the lift-off process. It was followed by 1000nm-thick bottom n^+ GaAs contact layer doped with Si to a concentration of $1.0\times10^{18}cm^{-3}$. Then the multiple QWs were grown. The QWs consisted of 50 periods of 50nm $Al_{0.25}Ga_{0.75}As$ as barrier and 5.5nm GaAs as well doped with Si, $7.0\times10^{17}cm^{-3}$. And finally, a 2μm n^+ GaAs top contact layer was doped to a concentration of $1.0\times10^{18}cm^{-3}$.

Using the above structure, the epitaxial GaAs/$Al_xGa_{1-x}As$ films were obtained by epitaxial lift-off (ELO) method. In the processing, a solution of 5g black wax (Apiezon W) dissolved in 40ml trichloroethylene was sprayed onto the as-grown QWIP sample and baked at 100℃ for 2 hours. The sample was then cleaved into a size of 5mm × 5mm and placed into 10% HF acid. After 10—20 hours, the AlAs release layer was etched away and the epitaxial film supported by the wax was floated off, as shown in Fig. 1. In the process, black wax acted as a mask to prevent the wafer being etched and to support the film before and after lift-off.

Once the process was completed, films supported by the wax can transfer to any clean new substrate. In our experiment, a Si substrate was used. Then a pressure about 0.15N/mm^2 was applied to the film to squeeze out the water[11]. After two days, the film would coalesce with surface of the new substrate due to the interfacial force that was called "van der waals" bonding. Finally the black wax was rinsed away in trichloroethylene leaving only the film bonded to the new substrate.

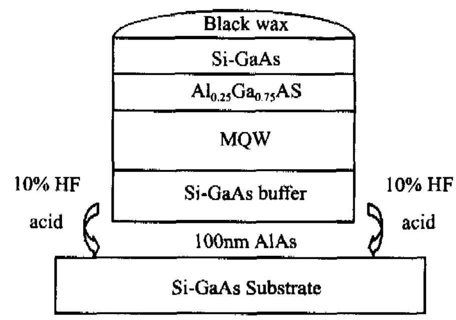

Fig. 1 Schematic diagram of epitaxial lift-off process
图1 外延层剥离的简单示意图

With the new sample and the as-grown sample, the 250μm × 250μm mesa devices were fabricated using standard GaAs lithography techniques and two-dimensional periodic gratings were made for normal incident light coupling. These two types of devices were used to check the degradation of lifted-off-QWIP material related to the as-grown-QWIP material. The top electrical contact made of AuGeNi was in the middle of the mesa with diameter d = 100μm. The bottom contact was also made of AuGeNi, as shown in Fig. 2.

2 Results and Discussion

2.1 Responsivity

We measured the blackbody responsivity of the lifted-off-QWIP device using a 500K blackbody as the IR source. The device was mounted in a liquid nitrogen Dewar (T≈80K). We obtained the responsivity $R_N = 1.7\times10^4 V/W$. The reference device of the same size fabricated from the as-grown wafer was also measured. The responsivity of the as-grown wafer device was $R_0 = 1.5\times10^4 V/W$. These two devices gave almost the same value of responsivity. The result confirmed that

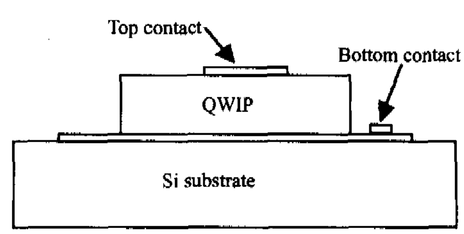

Fig. 2 Schematic diagram of QWIP
图2 器件结构示意图

the lifted-off-QWIP device still had good performance in IR detection and the lift-off process would not degrade the quality of QWIP material.

2.2 Photocurrent spectrum

The photocurrent a spectra of the lifted-off-QWIP device and the as-grown wafer device were also measured with a Fourier transform infrared spectrometer (FTIR) at 80K. Figure 3(a) and (b) gave the experimental results of the two devices as dots. Differences between the two devices were evident. The photocurrents in the figure were in arbitrary unit and were not comparable.

As shown in Fig. 3, the peak response wavelength of the as-grown wafer device was at 8.74μm while that of the lifted-off one is at 8.5μm. Based on effective mass approximation theory, the peak of photocurrent spectrum was expected at 8.9μm, which was in good agreement with the result of the as-grown wafer device. Also, we could see that the photocurrent spectrum of the as-grown wafer device shown in Fig. 3 (a) gave one peak behavior while the lifted-off-QWIP device shown in Fig. 3 (b) gave multi-peaks behavior. We think the differences in peak response wavelength and line shape between the two devices can be understood by the resonant absorption [12,13].

In the resonant absorption process, boundary conditions between layers as well as the dielectric functions for each layer would have great effect on the transmission of electro-magnetic wave along the multilayer quantum wells. The simulation can be done using transfer-matrix method (TRM). In this way, the substrate, the buffer layer, the active layer of MQW, and the ambient air can be included. In our simulation, the active MQW layer and the buffer layer (top and bottom contact) are treated as a single layer (effective medium approximation) with an effective dielectric function. The effective dielectric function can be written as:

$$\varepsilon(\omega) = \varepsilon_\infty + \frac{f\omega_p^2}{\omega^2 - \omega_0^2 + i\gamma\omega}, \quad (1)$$

here ω_p is the plasma frequency defined by $\omega_p = \left(\frac{\rho_s e^2}{\varepsilon\varepsilon_0 m^* a}\right)^{\frac{1}{2}}$, where a is well width, ρ_s is two-dimensional carrier density and ε is dielectric constant of the well. ε_∞ is average dielectric constant of the active layer. f is oscillator strength of the inter-sub-band transition and γ is relaxation energy. Thus, the structure we simulated before and after lift off is: air/QWIP/GaAs substrate (before) and air/QWIP/air/Si substrate (after). Here we assume that a very thin air layer is between the QWIP and the new Si substrate. This is a good approximation since "van der waals" bonding is not very tight. On the other hand, dust particles that have been trapped between the film and the Si substrate appear to raise tiny tent-like structures under the thin film and also make the bonding not very tight [11]. Our work is carried out in a normal laboratory environment rather than special clean room surroundings.

The simulated resonant absorbance $\alpha(\lambda)$ of the two different structures are calculated out as shown in Fig4 (a) and (b). Parameters in our simulation are: $d_{QWIP} = 5\mu m$ (thickness of QWIP structure), $f = 1$, $\omega_0 = 1140 cm^{-1}$ and $\gamma = 56 cm^{-1}$ for the as-grown wafer device, and $d_{QWIP} = 5\mu m$, $f = 0.8$, $\omega_0 = 1170 cm^{-1}$, $\gamma = 67 cm^{-1}$ and $d_{air} = 0.7\mu m$ (thickness of the air between QWIP and Si) for the lifted-off-QWIP device.

From Fig. 4 we can see that the line shape is very different for the two different structures. The lifted-off-QWIP device shows obvious resonant absorption and gives multi-peaks behavior in similar to the photocur-

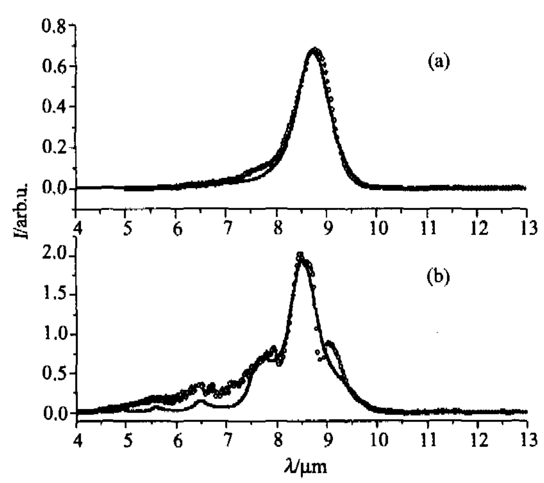

Fig. 3 Photocurrent (I) spectrum of two devices (a) as-grown-OWIP (b) lifted-off-QWIP. The dots and lines are the experimental and theoretical data

图3 未剥离器件和剥离后器件的光电流谱 (a) 未剥离器件;(b) 剥离后器件。圆点表示实验结果,实线表示理论计算结果

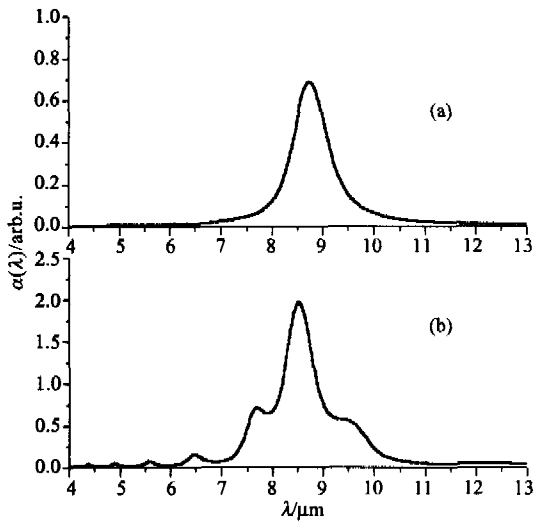

Fig. 4 The calculated absorption spectrum (a) The as-grown-QWIP (b) The lifted-off-QWIP
图4 理论计算的未剥离器件和剥离后器件的吸收光谱 (a) 未剥离器件 (b) 剥离后器件

rent spectrum. In the as-grown-QWIP structure, the difference of dielectric function value between the active layer and substrate is not so great. The reflection at the interface of GaAs substrate and active layer is rather small. Then the resonant absorption behavior is not strong. However, in the lifted-off-QWIP structure, the interface between active layer and air or Si will result in large reflection of light due to the large difference of the dielectric function value between active layer and air or Si. So that one can observe an obvious resonant absorption in the lifted-off-QWIP device.

Since the photocurrent response $I(\lambda)$ is proportional to absorption $\alpha(\lambda)$ and transmission coefficient of electron from QW to contact layer, $T_{eff}(\lambda)$, then one has:

$$I(\lambda) \propto \alpha(\lambda) \times T_{eff}(\lambda) \quad . \qquad (2)$$

As a good approximation, $T_{eff}(\lambda)$ can be described as: $\frac{1}{1+e^{(\lambda-\lambda_c)/\sigma}}$, where λ_c is the cutoff wavelength, and σ is 0.2 obtained by fitting the as-grown wafer device spectrum. Thus, the photocurrent spectrum can be easily calculated from Fig 4. The calculated curves are presented as solid lines in Fig 3. The simulated photocurrent lines of the two devices are in good agreement with their experiment data.

3 Conclusion

Epitaxial films of GaAs/AlGaAs multi-quantum wells were obtained by ELO method and devices with these films were fabricated and tested. The ELO method did not degrade the QWIP device performance. It gives a high possibility to integrate the QWIP with other photonic material. The resonant absorption has been observed in the photocurrent spectrum of lifted-off-QWIP device.

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