Photoemission performance of transmission-mode GaAlAs/InGaAs photocathode

HONGCHANG CHENG[a,b,c,*], QINGDUO DUANMU[a], FENG SHI[b,c], LEI YAN[b], LIU FENG[b], HUI LIU[b]
[a]*School of Science, Changchun University of Science and Technology, Changchun 130022, China*
[b]*Science and Technology on Low-Light-Level Night Vision Laboratory, Xi'an 710065, China*
[c]*North Night Vision Technology Group Co., LTD, Xi'an 710056, China*

In order to match the laser working at 1.06 μm, a GaAlAs/InGaAs photocathode material was grown by molecular beam epitaxial and was fabricated in the form of transmission-mode GaAlAs/InGaAs photocathode module. It is shown that the integral sensitivity is 575 $\mu A\cdot lm^{-1}$ and the radiant sensitivity at 1.06 μm is 0.043 $mA\cdot W^{-1}$ for the GaAlAs/InGaAs photocathode module. Comparing with the optical properties of the GaAs photocathode module and the photoemission performance curves of the other InGaAs photocathode respectively, it is indicated that the GaAlAs/InGaAs photocathode module prepared in this paper can respond shifting to the infrared waveband, the radiant sensitivity at 1.06 μm is higher than that of Russia's photocathode, and the integral sensitivity is higher than that of US Andor's photocathode. The results show that the parameters of the GaAlAs window layer and the InGaAs active layer should be improved to design in order to decrease the shortwave response and further increase the longwave response.

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1. Introduction

The near-infrared image intensifier is developed with transmission-mode (t-mode) GaAlAs/InGaAs photocathode whose spectral response can effectively match the night sky spectrum. The image intensifier is easy to combine with the laser working at 1.06 μm and forms a near-infrared long-range pulse gating night-vision system. Therefore, developing a GaAlAs/InGaAs photocathode has currently become a hot research subject.

US is the country that reports the research of InGaAs photocathode for the earliest and the most. In 1993, the US Litton System Inc applied for a patent on the InGaAs photocathode [1]; in 1995, it made supplementary application for the patent [2] on preparation method of the photocathode; in the same year, it published the dispersive infrared response (in the range of 1.0~1.3 μm) image intensifier [3]. The spectral response of t-mode GaAlAs/InGaAs photocathode can extend its long wavelength threshold to 1.06 μm, and the quantum efficiency over 900 nm is apparently higher than that of GaAs photocathode and S20 cathode [4]. Moreover, with the change of in component in the InGaAs active layer, the threshold of long wavelength will be different for the spectral response curve [5]. With the application of t-mode InGaAs photocathode, the research on its growing method develops at the same time, showing that molecular beam epitaxial (MBE) can grow a high-quality InGaAs photocathode material [6]. In 2002, US ITT reported the change of spectral response curve of t-mode InGaAs photocathode with the change of in component [7]. In 2005, Russia reported the development of t-mode InGaAs photocathode image intensifier, and the results showed that the integral sensitivity was 750 $\mu A\cdot lm^{-1}$ and the radiant sensitivity at 1.06 μm was 0.025 $mA\cdot W^{-1}$ [8].

This paper reports the development and test results of t-mode InGaAs photocathode material, module and photodiode of China whose experimental curves are compared with the optical properties curves of the conventional GaAs photocathode module and photoemission performance curves of US Andor's and Russia's InGaAs photocathode respectively. The result is of great significance on the design and preparation of infrared extended InGaAs photocathode modules.

2. Experiment and result analysis

2.1. Preparation of GaAlAs/InGaAs photocathode material

In the experiment, MBE was utilized to grow the GaA1As window layer on the GaAs substrate, and then to grow the InGaAs active layer thereon. The critical thickness with no mismatching is 200 Å when the In component value x in the $In_xGa_{1-x}As$ material is bigger than 0.1. However in this paper the thickness of the InGaAs active layer was designed to be 1 μm, so the heteroepitaxy of GaAlAs/InGaAs has misfit dislocation. Therefore, surface topography, four-crystal X-ray diffraction, PVS spectrum and electrochemical C-V tests were conducted on the GaAlAs/InGaAs photocathode material.

First, three-coordinate measuring machine was used to test the surface topography of the epitaxial wafer for the

$In_xGa_{1-x}As$ material with x=0.1, as shown in Fig. 1. It was the partial surface topography of InGaAs photocathode material that was magnified 100 times and the result indicated that the material surface had some cross-hatch.

Next, four-crystal X-ray diffraction instrument was used to conduct the test on the epitaxial wafer of the $In_xGa_{1-x}As$ with x=0.1, as shown in Fig. 2. It indicated that the diffraction peak of GaAs substrate was very large on the four-crystal X-ray diffraction curve; moreover, the InGaAs peak envelope also appeared in the curve, which illustrated that the prepared material coincided with the designed $In_xGa_{1-x}As$ transition layer.

Fig. 1. Surface of $In_xGa_{1-x}As$ epitaxial wafer (amplifying 100 times).

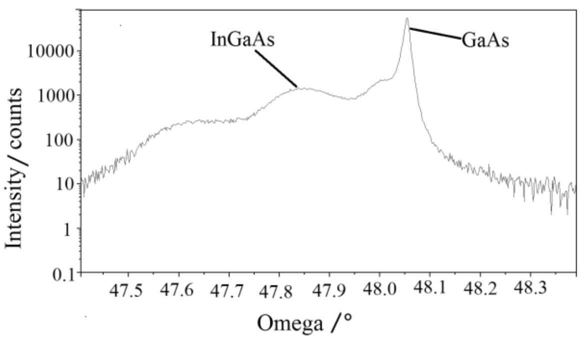


Fig. 2. Four-crystal X-ray diffraction curve of $In_xGa_{1-x}As$ epitaxial wafer

PVS testing instrument was employed to obtain the PVS spectrum of the GaAlAs/InGaAs photocathode material at 0.52 μm. As shown in Fig. 3, it could be seen that the infrared absorption was 1.318 eV which was the cut-off wavelength was over 940 nm.

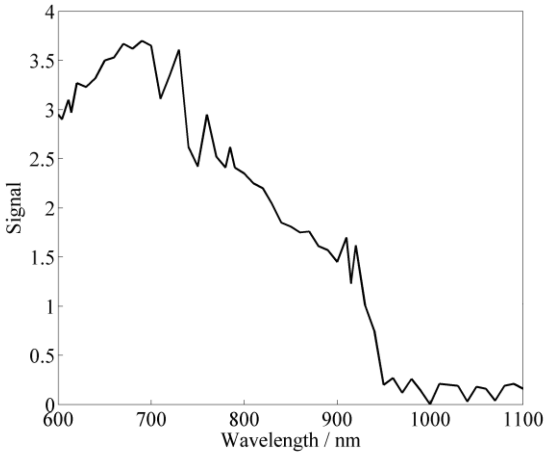


Fig. 3. PVS spectrum of $In_xGa_{1-x}As$ epitaxial wafer

The forbidden bandwidth of $In_xGa_{1-x}As$ material with the different in components can be acquired from the following formula,

$$E_g = 1.064(1-x) + 0.36 \tag{1}$$

where E_g is the $In_xGa_{1-x}As$ forbidden bandwidth and x is the in component. When the infrared absorption energy of InGaAs is 1.318 eV, the in component value can be computed to be 0.1 by Eq. (1), which is consistent with the designed value.

The electrochemical C-V tests can be conducted to acquire the structure thickness of all layers of epitaxial wafer of $In_xGa_{1-x}As$ and the doping concentration of current carrier, as shown in Fig. 4, indicating that the epitaxial wafer has a GaAlAs window layer with thickness of 0.3 μm and doping concentration of 2×10^{18} cm^{-3}, an InGaAs active layer with thickness of 0.9 μm and doping concentration of 1×10^{19} cm^{-3}, and a GaAlAs barrier layer with thickness of 0.2 μm and doping concentration of 2×10^{18} cm^{-3}. The interface of all layers is clear, and all doping concentrations reach the design parameter, but the thickness value is slightly different from the design value.

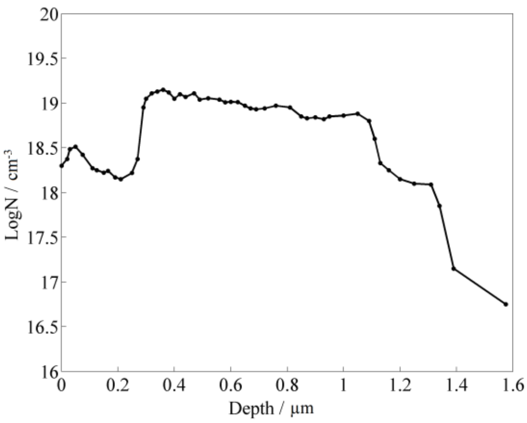


Fig. 4. The electrochemical C-V profiling of carrier concentration in $In_xGa_{1-x}As$ epitaxial wafer.

2.2. Preparation of GaAlAs/InGaAs photocathode module

With the aid of t-mode cathode module preparation technology, for the t-mode GaAlAs/InGaAs photocathode structure [9], a Si_3N_4 antireflection layer was firstly prepared on Corning 7056# glass window, and then the GaAlAs/InGaAs epitaxial layer was bonded to glass/Si_3N_4 by means of heat pressing. The t-mode GaAlAs/InGaAs photocathode module was prepared, included the glass substrate, the Si_3N_4 antireflection layer, the GaAlAs window layer, and the InGaAs active layer from top to bottom, as shown in Fig. 5.

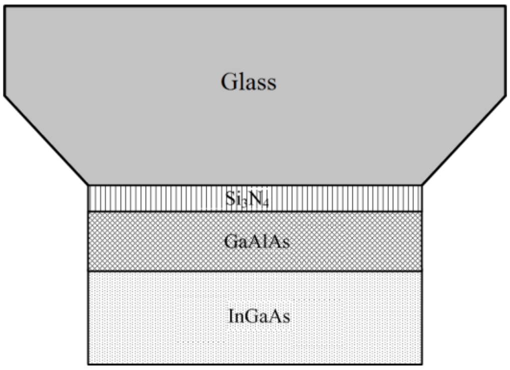
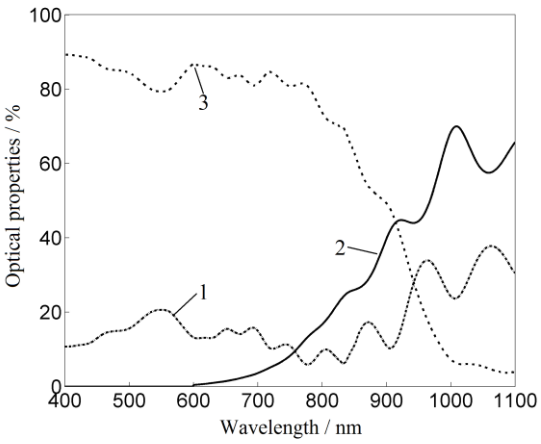


Fig. 5. Diagram of GaAlAs/InGaAs photocathode module.

A UV-Vis-NIR spectrophotometer typed UV-3600 was used to measure the reflectivity and the transmittivity of the GaAlAs/InGaAs photocathode module, and its absorptivity curve could be calculated simultaneously [10], as shown in Fig. 6.



Curve 1: The reflectivity; Curve 2: The transmittivity; Curve 3: The absorptivity.

Fig. 6. Optical properties curves of the GaAlAs/InGaAs photocathode module.

Cs-O deposition method was adopted to activate the GaAlAs/InGaAs photocathode module, and the whole activation process strictly followed the same activation technology specification of the GaAs photocathode module [11, 12]. The heat cleaning process was proceeded at the temperature of 600^0 C for the first time with heating up for two hours and keeping warm for one hour, and likewise, proceeded at the temperature of 400^0 C for the second time with heating up for one hour and keeping warm for 12 minutes. The activation began after heat cleaning two hours later, and the vacuum degree of the activation chamber was less than 1×10^{-8} Pa. During the activation, Cs source was provided firstly, and after appearing the photocurrent, Cs source and O source alternation started until the peak photocurrent reached the maximum value. After the activation, the spectral response curve of the photocathode was measured by the spectral response measurement instrument, as shown in Fig. 7.

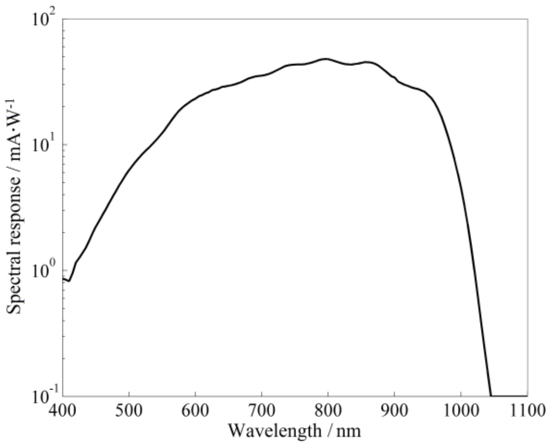
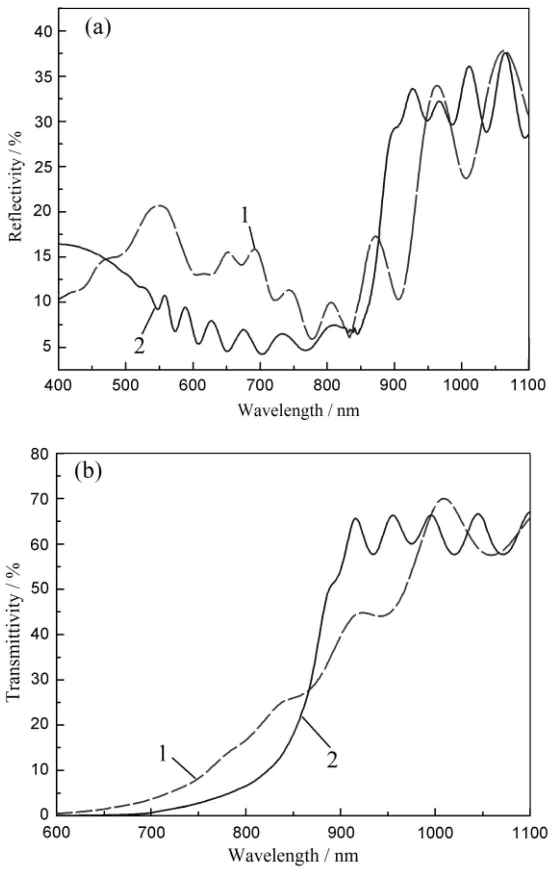


Fig. 7. Spectral response curve of GaAlAs/InGaAs photocathode module.

It indicated that the spectral response extended to more than 1 μm. According to the experimental curve, the integral sensitivity of the prepared GaAlAs/InGaAs photocathode was calculated as 575 $\mu A\cdot lm^{-1}$, and the radiant sensitivity at 1.06 μm was 0.043 $mA\cdot W^{-1}$.

3. Discussion

Compared with the conventional t-mode GaAs photocathode module, the GaAlAs/InGaAs photocathode module is mainly characterized in that the response wavelength extends towards the infrared waveband, which embodys the difference of the optical properties including the reflectivity and the transmisstivity. The reflectivity curves and the transmittivity ones of both the photocathodes are compared each other, as shown in Fig. 8(a) and 8(b).



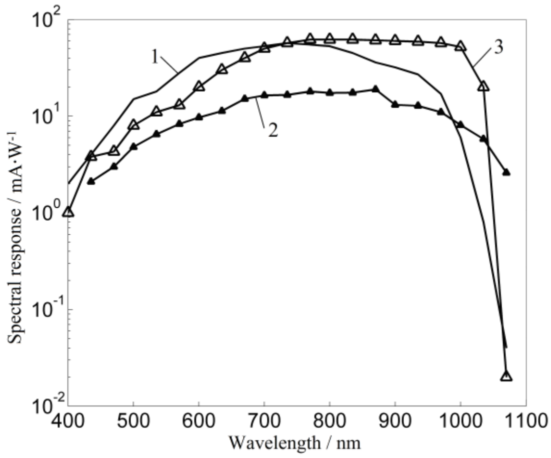
Curve 1: GaAlAs/InGaAs photocathode module; Curve 2: GaAs photocathode module

Fig. 8. Comparison of optical properties between GaAlAs/InGaAs and GaAs photocathode modules (a) The reflectivity curve; (b) The transmittivity curve.

The comparison on the reflectivity in Fig. 8(a) shows that, the range of the smallest points in the curve of the GaAlAs/InGaAs photocathode module obviously deviates from that in the curve of the GaAs photocathode module. The range of small reflectivity values of the conventional GaAs photocathode is between 550 nm and 850 nm, but that of the GaAlAs/InGaAs photocathode is between 750 nm and 950 nm. More obviously, the GaAs reflectivity curve begins to rise notably at the wavelength of 850 nm, while it is 900 nm for the GaAlAs/InGaAs photocathode. Therefore, the reflectivity curve shows that the infrared extended module evidently presents a better trend of extending towards the infrared region than the conventional GaAs module.

The same conclusion can be drawn from Fig. 8(b). The transmittivity curve of the GaAlAs/InGaAs photocathode is obviously lower than that of the GaAs photocathode in the range of 850~1000 nm. The low transmittivity indicates that more photons in the wave band are absorbed and thus the effective utilization rate is much higher, so the infrared extended module obviously presents a better trend of extending towards infrared waveband than the conventional module. To sum up the analysis results of the reflectivity and the transmittivity, the absorptivity cut-off wavelength of the GaAlAs/InGaAs photocathode module moves towards the longwave compared with that of the GaAs photocathode module. Therefore, the spectral response curve shall also move towards the infrared region.

After the module preparation and cathode activation, the GaAlAs/InGaAs photocathode was prepared as a photodiode whose spectral response curve was contrasted with those of US Andor's and Russia's InGaAs photocathodes, as shown in Fig. 9. There are three spectral response curves of the InGaAs photocathodes which are from North Night-Vision Technology Group Co., Ltd. (NNVTG) in 2010 (that is the sample in this paper), Andor in 2006 and Russia in 2005 respectively.



Curve 1: NNVTG in 2010; Curve 2: Andor in 2006; Curve 3: Russia in 2005
Fig. 9. Comparison in spectral response curves of three InGaAs photocathode modules.

The integral sensibility can be calculated by the spectral response value of the GaAlAs/InGaAs photocathode module, with the formula shown below [13]:

$$S_i = \frac{I}{\Phi_v} = \frac{\int_0^{\infty} S(\lambda)W(\lambda)\,\mathrm{d}\lambda}{683\int_{380}^{780} V(\lambda)W(\lambda)\,\mathrm{d}\lambda} \tag{2}$$

where S_i is the integral sensibility of the photocathode, I is the photocurrent generated by the photocathode, Φ_v is the luminous flux when the standard light source irradiates on the photocathode plane, $V(\lambda)$ is the spectral luminous efficiency of human eye (that is also called the visibility function), $W(\lambda)$ is the radiant spectrum distribution of the standard incident light source, $S(\lambda)$ is the spectral response of the photocathode at the wavelength of λ. The values of $W(\lambda)$ and $V(\lambda)$ are taken from Ref. [14] and [15] respectively. Thus, the integral sensibility and the radiant sensibility of three curves in Fig. 9 can be obtained and listed in Table 1.

Table 1. Comparison of spectral response performance parameters of three InGaAs photocathode modules.

Sample	NNVTG in 2010	Andor in 2006	Russia in 2005
Integral sensitivity ($\mu A\cdot lm^{-1}$)	575	≈300	872
Radiant sensitivity at 1.06 μm ($mA\cdot W^{-1}$)	0.043	0.1	0.025
Longwave threshold (μm)	1.06	>1.1	1.1

The curves in Fig. 9 show that the spectral response of the GaAlAs/InGaAs photocathode module developed by NNVTG in 2010 is evidently higher than that of Andor and Russia at the short wavelength less than 735 nm, which is unfavorable for the infrared extended response. The relatively high shortwave response is attributed to the improper thickness and A1 component value of the GaAlAs window layer. In the range of 735~1000 nm, the spectral response of NNVTG's GaAlAs/InGaAs photocathode module is lower than that of Russia's module and higher than that of Andor's module. In the case of the radiant sensibility at 1.06 μm, NNVTG's photocathode module is inferior to Andor's module but superior to Russia's module. The low response at the long waveband is connected to the thickness, the doping concentration and especially the in component in the InGaAs layer. The small in component will constrain the spectral response at the long waveband. In Table 1, the integral sensibility of NNVTG's GaAlAs/InGaAs photocathode module is much higher than that of Andor's one, but still has certain distance from that of Russia's one. Therefore, the structure parameters of the GaAlAs layer and the InGaAs layer need to be adjusted in order to decrease the shortwave response of the GaAlAs/InGaAs photocathode and increase the longwave response and the integral sensibility.

4. Conclusion

The GaAlAs/InGaAs photocathode material was grown by MBE and prepared in the form of t-mode photocathode module. The surface topography, four-crystal X-ray diffraction, PVS spectrum and electrochemical C-V tests were conducted on the photocathode material. The reflectivity, the transmittivity, and the spectral response were measured on the photocathode module. The experimental results show that all parameters of the growing material meet the designed requirement, the integral sensibility of the module is 575 $\mu A\cdot lm^{-1}$, and the radiant sensibility at 1.06 μm is 0.043 $mA\cdot W^{-1}$. The comparison with the optical properties of the conventional GaAs photocathode module shows that the absorptivity cut-off wavelength of the GaAlAs/InGaAs photocathode deviates from the short wavelength and presents the response shifting to the infrared waveband. Comparing with the spectral response curves of the Andor's InGaAs photocathode and the Russia's one, it indicated that the shortwave response of the photocathode developed by NNVTG in 2010 is high, the radiant sensibility at 1.06 μm is higher than that of the Russia's module and lower than the Andor's module, but the integral sensibility is much higher than that of Andor. Therefore, the parameters and preparation technology of the GaAlAs window layer and the InGaAs active layer should be improved in further research in order to increase the infrared response of the GaAlAs/InGaAs photocathode.

Acknowledgements

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*Corresponding author: chh600@163.com