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Metallic cavity quantum well infrared photodetector for filter-free SF₆ gas imaging

Xiaofei Nie^{1,2} · Yizhe Yin^{1,3} · Honglou Zhen^{1,2*} · Xiaohao Zhou^{1,2} · Pingping Chen^{1,2}

Abstract

Generally, for gas imaging, narrowing the response of the camera sensor around the target gas's absorption band would increase the imaging contrast. In this paper, A filter-free narrowband metallic cavity quantum well infrared photodetector is proposed. The metallic cavity is formed by Ti/Au film coating on the detector's mesa. The geometry of the cavity is properly designed to sustain cavity mode resonating at 10.6 μm . With strong resonance, the absorption efficiency of the embedded quantum well active layer maintains high level ($\sim 74\%$) even with a fairly low doping concentration ($\sim 1 \times 10^{17} \text{cm}^{-3}$). And the bandwidth is as narrow as 0.22 μm . A waveguide model is presented and used to analyze the metal cavity quantum well infrared photodetector, and it is found that the metal film coating on the side wall played an important role in enhancing the resonance and narrowing the spectral line width.

Keywords Infrared gas imaging · Quantum well · Metallic cavity · Narrowband

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Declarations

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Conflicts of interest

The authors declare that they have no conflict of interest.

Author's contributions

Xiaofei Nie and YiZhe Yin contributed equally to this work.

Xiaofei Nie and Honglou Zhen conceived the device design. Xiaofei Nie and Yizhe Yin performed the simulation. Xiaohao Zhou performed the calculation of dark current. Xiaofei Nie and Honglou Zhen wrote the manuscript with input from all authors. All authors contributed to the data analysis and discussions and approved the final manuscript.

1 Introduction

Gas imaging has proven to be a superior remote-sensing technique for detecting and locating an invisible gas plume (Strachan et al. 1985; McRae and Kulp 1993; Althouse and Chang 1995; Bennett et al. 1995; Hinnrichs and Massie 1995; Kulp et al. 1997; Hinnrichs 1999; Hodgkinson and Tatam 2012; Hinnrichs and Jensen 2013; Hinnrichs and Hinnrichs 2017; Ravikumar et al. 2017; Xu et al. 2018; Olbrycht and Kaluza 2019; Zhang et al. 2011; Gålfalk et al. 2016). The basic of gas imaging is the detectable electromagnetic radiation difference between the gas plume and the ambient background. Gas can be imaged either against a cold background imaging the gas emissions or against a warm background imaging the gas absorption.

Generally, the greater the temperature difference and/or the higher the gas concentration, the clearer the gas image. Because many gases have their own inherent absorption bands in the infrared range. For example, the insulating gas SF₆ has a narrow absorption band (less than 200 nm) near 10.6 μm . Therefore, in practical applications, this characteristic absorption band is usually used for SF₆ gas leakage detection. And moreover, the response bandwidth of the detector is also limited to a narrow band to improve imaging contrast (Vollmer et al., 2006; Vollmer and Möllmann, 2010).

Existing gas imaging cameras usually use narrow-band technology to detect the radiation around the absorption band of the target gas. Narrowband detection has demonstrated that the ability of distinguishing the gas plume from the background could be significantly improved (Hinnrichs and Gupta 2008; Olbrycht and Kaluza 2019). As illustrated in Fig. 1a, it is reasonable that a detector with a narrowband response of $R1(\lambda)$ is more sensitive to the radiation difference caused by the existence of SF₆ comparing with a detector with that of $R2(\lambda)$.

Generally, narrowband detection is achieved by assembling a dispersive element or filter in front of the detector pixel array to disperse or filter the incident light. All these additional components require the necessary space for installation, and also require additional cooling power to reduce their own infrared radiation, which is especially critical for gas detection in the long-wavelength infrared band. Though several micro-filters (Lu et al. 2009; Li et al. 2016) which could be integrated with the sensor pixel have been developed (this is considered to be the key point to miniaturization of imaging systems),

such as the Fabry-Pérot filter (Neumann et al. 2008; Frey et al. 2015; Mao et al. 2016; Xu et al. 2017) and the plasmonic filter (Genet and Ebbesen 2007; Liang et al. 2017; Wang and Dan 2018; Dao et al. 2019; Xu et al. 2019), most of their bandwidths are still broad at infrared band, approximately 1 μm around 10.6 μm wavelength.

Quantum well infrared photodetectors (QWIPs) are especially suitable for gas imaging, such as SF_6 gas imaging (Sun et al. 2017; Hinnrichs and Gupta 2008). Supposing the pixels of the camera have a narrowband response, the monochrome image could be directly generated by the pixel array without using any disperse lens or filter. With the narrowband response of the pixels locating at the absorption band of the target gas, the radiation difference between the gas plume and the background could be easily detected by the pixels, as shown in Fig. 1b. There have been some efforts on developing narrowband detector with QWIP, such as the multispectral QWIP with diffractive resonant optical cavities (DROCs) (Mitra et al. 2003a; Mitra et al. 2003b), the quantum grid infrared photodetectors (QGIPs) (Choi et al. 2003; Choi et al. 2004) and the resonator QWIP (R-QWIP) (Sun et al. 2017). However, the full width at half maximum (*FWHM*) of the achieved narrowband responses have never been narrower than 1 μm around 10.6 μm wavelength.

Fig. 1 (a) The transmittance spectrum of SF₆ and the response spectra of two detectors with different bandwidths. **(b)** Schematic of narrowband detector for SF₆ gas imaging. The bar of gray scale indicates the signal strength of the pixel

2 Design of a filter free narrowband detector

2.1 Design of detector structure

In this paper, a metallic cavity quantum well infrared photodetector (MC-QWIP) for narrowband detection is proposed. The mesa structure of the MC-QWIP is shown in Fig.2a. The metallic cavity formed by Ti/Au coating on the mesa could be regarded as a 2-dimensional rectangular cavity. Its resonating cavity modes can be easily tuned by the mesa size (Nie et al. 2020). The resonant wavelength of the metallic cavity and the absorption peak of the embedded quantum well active layer were both adjusted at 10.6 μm . According to the finite element method (FEM) simulations, an absorption spectrum with *FWHM* as narrow as 0.17 μm has been achieved by the designed MC-QWIP. Furthermore, the calculated dark current demonstrates that such MC-QWIP has the advantage of maintaining high quantum efficiency at low doping concentration which is considered important for reducing the dark current of the device and thus improving the signal-noise ratio of the camera system.

Fig. 2 (a) Schematic of the MC-QWIP. (b) Conduction band structure of the GaAs/Al_{0.21}Ga_{0.79}As quantum well and the subband wavefunctions ψ_1 and ψ_2 . (c) The calculated absorption coefficient profile $\alpha(\lambda)$ of the QWs with different doping concentrations. (d) The simulated absorption quantum efficient of the QWs with different doping concentrations

As shown in Fig. 2a, the QWIP material consists of a quantum well active layer sandwiched between a top and a bottom contact layer. The QW active layer consists of 21 periods of 6.9 nm GaAs /50nm Al_{0.21}Ga_{0.79}As with total thickness of 1.2 μm . The calculated conduction band structure and the subband wavefunctions (Harrison and Valavanis 2016) are shown in Fig. 2b. The intersubband transition energy of 116.9 meV results in an expected QW absorption peaking at 10.6 μm .

The mesa structure of the MC-QWIP was designed as shown in Fig. 2a. The metallic cavity was formed by Ti/Au film coating on the mesa. Several grooves on the top of the mesa are used to couple more incident light into cavity mode. The HfO₂ film was used to prevent short circuit caused by the Ti/Au layer on the sidewall. The embedded quantum well active layer was tuned to absorb specific band around 10.6 μm . Because of its low absorption efficiency, when the infrared light illuminates the cavity from the bottom, it can

be expected that the light at resonance would bounce many times within the cavity before it is completely absorbed and escaped. Thus, the absorption response at resonant wavelength would stand out from the base spectrum, resulting in a narrowband response. Based on such a concept, a filter-free narrowband detector of pixel-sized was designed.

2.2 Simulation and analysis

Finite element method (FEM) was used to simulate and optimize (Choi et al. 2012, 2011; Choi 2012) the MC-QWIP. Drude model of gold was used to describe the permittivity of Ti/Au layer (thickness of 300 nm) in the simulation. The refraction indexes of the QWIP material (n_{GaAs}) and the HfO_2 film (thickness of 50 nm) were assigned as 3.24 and 2 respectively. The QW active layer was treated as an effective anisotropic absorbing medium. Its absorption profile $\alpha(\lambda)$ was estimated by (Choi 1997; Helm 1999)

$$\alpha(\lambda) = \frac{n_D w}{L} \frac{e^2 \hbar}{2 n_{GaAs} \epsilon_0 m^* c} f_{12} \frac{\Gamma}{(E_2 - E_1 - \hbar \omega)^2 + \Gamma^2} \quad (1)$$

where n_D is the doping concentration in the well, w is the well width, L is the QW period, f_{12} is the dimensionless oscillator strength, $m^* = 0.067m_0$ is the effective mass, and Γ is the half width at half maximum ($HWHM$) of the Lorentzian spectrum. In the calculation, f_{12} was set as 1 and Γ was set as 6 meV. The calculated $\alpha(\lambda)$ spectra with doping concentration being $8.0, 4.0, 2.0, 1.0$ and $0.5 \times 10^{17} \text{cm}^{-3}$ respectively were shown in Fig. 2c. The full width at half maximum ($FWHM, \Delta\lambda$) of all the spectra is $1.1 \mu\text{m}$.

Based on these material parameters, we modeled the electromagnetic field distribution within the MC-QWIP under x-polarized plane wave incidence. Then the absorption efficiency (or inner quantum efficiency, QE) could be evaluated by the following equation (Choi et al. 2012, 2011; Choi 2012):

$$QE = n_{GaAs} \alpha(\lambda) t_a \frac{\overline{|E_z|^2}}{|E_0|^2} \quad (2)$$

where t_a is the thickness of the QW active layer, E_z is the vertical electric component and E_0 is the electric field of the incident light. The average E_z squared is evaluated in the volume of the QW active layer.

Figure 2d shows the absorption efficiency of the QW active layer in an optimized MC-QWIP. The mesa width is $21 \mu\text{m}$ and the total material thickness is $3.1 \mu\text{m}$. Six grooves with period of $3.5 \mu\text{m}$ and depth of $0.5 \mu\text{m}$ are on the mesa top. The maximum QE

is 74%, which is the peak QE of the spectrum (green curve) with $n_D = 2 \times 10^{17} \text{ cm}^{-3}$. When the doping concentration decreases by half, the maximum QE remains almost constant while the $FWHM$ decreases. There exists an optimum doping concentration (or doping concentration range) for achieving maximum QE . While for $FWHM$, the lower the doping concentration, the narrower the absorption spectrum. The spectral profile could be also evaluated by the quality factor (Q -factor), which is defined as the ratio of the peak wavelength (λ_{peak}) and the $FWHM$ ($\Delta\lambda$), i.e. $Q\text{-factor} = \lambda_{peak}/\Delta\lambda$. Thus, for a fixed peak wavelength, the higher the Q -factor, the narrower the absorption spectrum. The Q -factors extracted from the spectra in Fig. 2d are shown as circles in Fig. 3a.

Fig. 3 The simulated (a) absorption quantum efficient QE , (b) reflectivity R of the MC-QWIP and absorptivity A_{Au} of the Ti/Au layer at wavelength of $10.6 \mu\text{m}$ versus the doping concentration n_D . The Q -factors of MC-QWIP (black circles) are extracted according to the spectra in Fig. 2d and that of R-QWIP (red circles) are extracted from reference (Sun et al. 2017). The diameter of the circles indicate the Q -factor values. The

blue curves in (a) are the dark currents versus doping concentration calculated at 60 K and 70 K temperature. The insets in (b) are E_z/E_0 distributions (ranges in ± 4 for $n_D = 0$ and ± 0.6 for $n_D = 10$)

In order to conduct a complete investigation, further simulation was performed at the wavelength of 10.6 μm , with doping concentrations ranging from 0.1 to 10 (10^{17}cm^{-3}) and shown in Fig.3. The corresponding results of R-QWIP extracted from reference (Sun et al. 2017) are also shown in Fig. 3(a) (the red dashed curve and red circles). The dark current induced mainly by thermionic emission current is related to the density of electrons n_{th} and the average drift velocity v_d , and can be expressed as (Gunapala et al. 1991),

$$I_d = eA_d v_d n_{th} \quad (3)$$

where e is the elementary charge, A_d is the device detector area, and

$$v_d = \frac{uF}{\sqrt{1 + \left(\frac{uF}{v_{sat}}\right)^2}} \quad (4)$$

and

$$n_{th} = \frac{m^* k_B T}{\pi \hbar^2 L} e^{-\frac{E_{cf} - E_F}{k_B T}} \quad (5)$$

In equation (4), u is the electron mobility, F the electric field, v_{sat} the saturation velocity; in equation (5), m^* is the effective mass of GaAs, $\hbar$ the reduced Plank constant, k_B the Boltzmann constant, T the temperature, and E_{cf} the cutoff energy related to the cutoff wavelength. The Fermi level E_F , can be determined from the well two-dimensional doping density (assuming completely ionized) by

$$N_{2D} = \left(\frac{m^*}{\pi \hbar^2}\right) E_F \quad (6)$$

The calculated dark currents at temperatures of 60 K and 70 K were shown in Fig. 3a with blue curves.

We can see that for the MC-QWIP, there is an optimal doping concentration for achieving maximum QE . Furthermore, a wide range of doping concentrations ($0.6 - 4 \times 10^{17}\text{cm}^{-3}$) could maintain the QE beyond 60% giving rise to a robustness for varying doping concentration. The regularities of the R-QWIP (Sun et al. 2017; Choi et al. 2015) are much different from the results of the MC-QWIP. The simulated QE of the R-QWIP (Sun et al. 2017) is proportional to the doping concentration and ranges from 30% to 70% when the doping concentration increases from $0.2 \times 10^{18}\text{cm}^{-3}$ to $1.0 \times 10^{18}\text{cm}^{-3}$. The

FWHMs of their *QE* spectra remain basically unchanged for different doping concentration, resulting in a series of nearly constant *Q-factors*, as shown by the red circles in Fig. 3a. These results imply that the R-QWIP does not have the advantage of narrow-band detection. Besides, due to the proportional relationship with the doping concentration, the increase of its quantum efficiency is also accompanied by a large increase in dark current, which has been experimentally confirmed (Sun et al. 2017). While for the MC-QWP, we can see that as the doping concentration decreases from 10 to 1 (10^{17}cm^{-3}), the quantum efficiency reaches its highest value and then maintains high level, and, meanwhile, the dark current decreases by more than one order of magnitude. This indicates a great improvement in the signal-to-noise ratio and shows potential in raising operating temperature for QWIP devices (Choi et al. 2003).

Combining the absorptivity of the Ti/Au layer and the reflectivity of the MC-QWIP given in Fig.3b, we can reach the conclusion easily that the decrease of the *QE* at the lower doping is due to the increase of the absorptivity of the Ti/Au layer, while at the higher doping it is due to the high reflectivity of the MC-QWIP.

2.3 Analysis with waveguide model

Fig. 4 Schematic of (a) a waveguide, (b) the MC-QWIP and (c) the R-QWIP. The red regions indicate the QW active layers and the blue arrows indicate rays of incident light. (d) Calculated propagation length L for a beam of light propagating in the waveguide or the MC-QWIP

Here we make an analogy between the waveguide and the MC-QWIP to analyze the influence of the doping concentration on the QE and find out the cause of the difference between our MC-QWIP and the R-QWIP. The structures of the waveguide, the MC-QWIP and the R-QWIP are schematically shown in Fig. 4(a-c). The absorption in a waveguide shown in Fig. 4a can be estimated by (Helm 1999; Choi 2012)

$$QE \approx T_s \frac{\cos \theta}{2} \left(1 - e^{-\alpha(\lambda) \sin^2 \theta \frac{Mt_a}{\cos \theta}} \right) \quad (7)$$

where $T_s = 4n_{GaAs}/(1+n_{GaAs})^2$ is the transmittance of the GaAs substrate, $\cos \theta$ account for the projected area of the QW active layer in the light propagation direction, the factor $1/2$ indicate that only half of the incident light could contribute to the QW absorption, M is the number of the light passes through the QW active layer and can be calculated by

$$M = \frac{L_m}{t_m \tan \theta} \quad (8)$$

where L_m and t_m are the length and thickness of the waveguide material respectively. When M is taken as 2, Eq. (7) is consistent with the classical model by Choi (2012), which is used to estimate the QE of the edge coupled QWIP.

According to Eq. (7) and (8), in a long enough waveguide, the length L of the light propagating until decaying to $1/e$ is given by

$$L = Mt_m \tan \theta = \frac{t_m}{\alpha(\lambda) \sin \theta t_a} \quad (9)$$

For the MC-QWIP, if L is shorter than the mesa width, the light will be largely dissipated before experiencing a half cycle in the metallic cavity. The resonance effect will be much weaker. The critical angle for total inner reflection is about 18° for the QWIP material with refraction index of 3.24. Thus, the light with θ larger than 18° will be trapped in the cavity. Taking $\theta = 30^\circ$, we get $L = 19.8, 39.7, 79.3, 158.7$ and $317.4 \mu\text{m}$ for MC-QWIP with $n_D = 8, 4, 2, 1$ and $0.5 \times 10^{17} \text{ cm}^{-3}$ respectively. The lower the doping concentration, the longer the propagation length or the more intra-cavity circulation. The length L for other angles and doping concentrations is shown in Fig. 4d. The smaller the angle θ , the longer the length L . Ideally, the incident light will be completely dissipated in the cavity as long as $\theta > 18^\circ$, as shown in Fig. 4b, which will result in a constant QE for the QW active layer. However, due to the absorption of the metallic wall and the diffraction of the grooves, there is a competition between such light loss and the QW absorption. For a fixed angle θ , the length L increases exponentially with the decrease of n_D , as shown in Fig. 4d. Thus, the light cycle in the MC-QWIP increases rapidly at lower n_D . Because the absorption coefficient of the metallic wall is constant, the more light cycles, the more light losses on the metallic wall. This reveals the cause of the increasing absorptivity of the Ti/Au layer at lower n_D .

As shown in Fig. 4c, due to the diffraction of the grating, part of the reflected diffraction light near the top metal is more likely to become horizontal and transmit through the side wall after multiple reflections, while another part of the reflected diffraction light may escape from the bottom. The light in such a resonator cannot cycle too many times even though the QW active layer has a low doping concentration. Thus, the resonance effect is weak and the QW absorption decreases with the decreasing doping concentration while the bandwidth basically remains unchanged. This is the case of the R-QWIP (Sun et al. 2017;

Choi et al. 2015). As to the MC-QWIP, due to the reflection on the Ti/Au side wall, the number of the light passes through the QW active layer is more than that in the R-QWIP. That's why the MC-QWIP can maintain a relative high $QE(\lambda_{\text{peak}})$ at low doping concentration. As for the decrease of the $QE(\lambda_{\text{peak}})$ at high doping concentration, we attribute it to the increase of the light escaping from the bottom. At low doping concentrations, the light escaping from the bottom may be canceled out due to destructive interference, thus manifesting as low reflection at the bottom interface of the device (see the insets of Fig. 3b). However, at high doping concentrations, it can no longer be largely canceled out due to the reduction of light cycles (see the insets of Fig. 3b). Therefore, the QE decreases with the increase of the reflectivity at higher doping concentration as shown in Fig. 3.

3. Summary

In summary, due to the metallic film coating on the side wall, the incident light at resonance would recycle multiple times in the MC-QWIP. The simulations show that the $FWHM$ of the QW absorption can be as narrow as $0.17\ \mu\text{m}$. For narrowband and high QW absorption, the needed doping concentration is fairly low ($\sim 1 \times 10^{17}\text{cm}^{-3}$), leading to at least one order of magnitude decrease for the dark current comparing with normally doping ($\sim 1 \times 10^{18}\text{cm}^{-3}$) QWIP. A detector aiming to realize filter-free SF_6 gas imaging thus can be designed with the MC-QWIP. Besides, the resonating cavity modes can be easily tuned by the mesa size. Detectors that aim to detect the other infrared band can be easily designed accordingly.

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Figures

Figure 1

(a) The transmittance spectrum of SF₆ and the response spectra of two detectors with different bandwidths. (b) Schematic of narrowband detector for SF₆ gas imaging. The bar of gray scale indicates the signal strength of the pixel

Figure 2

(a) Schematic of the MC-QWIP. (b) Conduction band structure of the GaAs/Al_{0.21}Ga_{0.79}As quantum well and the subband wavefunctions ψ_1 and ψ_2 . (c) The calculated absorption coefficient profile $\alpha(\lambda)$ of the QWs with different doping concentrations. (d) The simulated absorption quantum efficient of the QWs with different doping concentrations

Figure 3

The simulated (a) absorption quantum efficient QE, (b) reflectivity R of the MC-QWIP and absorptivity A_{Au} of the Ti/Au layer at wavelength of $10.6 \mu\text{m}$ versus the doping concentration n_D . The Q-factors of MC-QWIP (black circles) are extracted according to the spectra in Fig. 2d and that of R-QWIP (red circles) are extracted from reference (Sun et al. 2017). The diameter of the circles indicate the Q-factor values. The

blue curves in (a) are the dark currents versus doping concentration calculated at 60 K and 70 K temperature. The insets in (b) are E_z/E_0 distributions (ranges in ± 4 for $n_D = 0$ and ± 0.6 for $n_D = 10$)

Figure 4

Schematic of (a) a waveguide, (b) the MC-QWIP and (c) the R-QWIP. The red regions indicate the QW active layers and the blue arrows indicate rays of incident light. (d) Calculated propagation length L for a beam of light propagating in the waveguide or the MC-QWIP