High performance InGaAs/InP avalanche photodiode integrated with metal-insulator-metal microcavity

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Abstract
Reducing the dark current of InGaAs/InP avalanche photodiodes (APDs) is an important way to improve its performance. Decreasing the active size can reduce the dark current but sacrifice the quantum efficiency. In this paper, the metal–insulator-metal (MIM) microcavity is integrated with an APD, which can converge light from tens of micrometers to several micrometers, so as to compensate for the loss of detection efficiency caused by the reduction of the size of the APD. Through photoelectric joint simulation, the optical response of the device can be obtained, and the coupling effect between the MIM structure and the APD can be analyzed directly. The simulation results show that the photocurrent to the dark current ratio of the APD integrated with the MIM microcavity is twice of the MIM free traditional APD, and the 3 dB bandwidth reaches 5.8 GHz. When the MIM microcavity is applied to an APD array, the optical crosstalk between pixels is found to be negligible.

Keywords Avalanche photodiodes · Photoelectric co-simulation · Metal–insulator-metal microcavity · Crosstalk

1 Introduction
High sensitivity avalanche photodiodes (APDs) are the core component of single photon detection, which are mainly used for quantum key distribution (Albota et al. 2006; Liao et al. 2017) and 3D lidar detection (Marinelli et al. 2018; Yu et al. 2017). Compared with traditional Si APDs, InGaAs/InP APDs have better single photon detection performance.
in the wavelength range of 1000–1600 nm. However, the inherent material defects lead to higher dark count rates (Qiu et al. 2015), which lead to a lower signal-to-noise ratio. Therefore, it is urgent to find an effective method to reduce the dark current (Robert et al. 2009), such as reducing the size of an APD (Carrano et al. 2009), but at the expense of the optical response. In this case, optical lenses are used to compensate for the loss of optical response (Wen et al. 2016; Ou et al. 2018; Sun et al. 2012; Ni et al. 2013). However, in order to obtain a smaller optical spot, the traditional optical lens usually requires a larger diameter and a smaller focal length (Piotrowski et al. 2003; Li et al. 2013; Giuseppe et al. 2015; Petter et al. 2020). At the same time, due to the separation from the APD, it is a huge challenge to achieve a high coupling efficiency (Giuseppe et al. 2015; Petter et al. 2020). In this paper, a metal insulator metal (MIM) optical microcavity is directly integrated on the APD, which is reported in detail in (Wen et al. 2017). The MIM microcavity can collimate and focus the incident light to several microns, and have a high optical transmittance, which provides an effective way to reduce the APD’s active diameter to several microns while maintaining a high optical response. Based on the photoelectric joint simulation, the performance of an APD integrated with the MIM microcavity is analyzed directly from the perspective of photoelectric response and the optimal coupling conditions are optimized.

2 Structure and simulation

Figure 1a shows the schematic diagram of an InGaAs/InP APD integrated with a MIM microcavity, denoted as MIM-APD. The MIM cavity is directly fabricated on the APD, which consists of three layers: the top Au grating layer, the middle SiO₂ insulator layer, and the bottom Au double slit layer. The lateral boundaries of the cavity are blocked by Au plate, as shown in Fig. 1b. The thickness of Au bars is \( t_1 = 100 \text{ nm} \), and the insulator is composed of \( t_2 = 300 \text{ nm} \) thick SiO₂. The period of the metallic grating is \( p = 1120 \text{ nm} \), and the Au bar width is \( w = 680 \text{ nm} \). The period number of the top grating \( N \) is set as 19, and the total length of the MIM cavity along the \( x \)-axis is 21 \( \mu \text{m} \). The enhancement factor of the MIM structure tends to be saturated when \( N \) is greater than 30, which is reported in detail in (Wen et al. 2016). To get better coupling efficiency, \( N \) should be controlled within 30. For the sake of computation, we fix \( N \) as 19. An InGaAs/InP APD with a separate absorption, grading, charge, and multiplication (SAGCM) structure is denoted in Fig. 1c. The thicknesses of the multiplication layer, charge layer, and absorption layer are kept as 0.8 \( \mu \text{m} \), 0.1 \( \mu \text{m} \), and 1.5 \( \mu \text{m} \), respectively.

To accurately simulate the optoelectronic coupling effect of the MIM microcavity and the APD, the photoelectric joint simulation is used. First the optical simulation of the MIM-APD is carried out with Ansys Lumerical’s Finite Difference Time Domain (FDTD) module (Dennis 2013; Lumerical 2020). TM light with the polarization along \( x \)-direction is vertically incident from the top Au grating layer, with a wavelength of 1550 nm, and the power is 10.5 nW. In the optical simulation of the MIM-APD, the photogenerated carrier rate (in the unit of \( \text{cm}^{-3} \text{s}^{-1} \)) in the absorption layer is calculated as the following Eq. (1) (Crocherie et al. 2009):

\[
G_{\text{opt}} = -\frac{\text{Re}(\nabla \cdot \mathbf{P})}{\hbar \nu} = \frac{\sigma |E|^2}{\hbar \nu}
\]

(1)

where \( \mathbf{P} \) is the Poynting vector, \( \hbar \) is the reduced Planck constant, \( \nu \) is the frequency of light in the absorption layer, \( \sigma \) is the electrical conductivity of the material, and \( E \) is the electric
field intensity. Here, we assume that each photon in the APD absorption layer produces an electron–hole pair.

Then the electrical simulation of the APD is performed through the CHARGE module based on carrier drift–diffusion equation and Poisson equation (Dennis 2013). During the calculation of drift and diffusion current, the simulation also considers the carrier recombination, including Shockley–Read–Hall recombination (SRH), Auger recombination, Radiation recombination, Band-to-band tunneling and Impact ionization (Hurkx et al. 1992; Selberherr 1984). The impact ionization is calculated by the Selberherr model:

$$R_{\text{II}} = \frac{\alpha_n J_n}{e} + \frac{\alpha_p J_p}{e}$$

(2)

In which, $R_{\text{II}}$ is the generation rates caused by the collision ionization of carriers, $J_n$ and $J_p$ are the current densities of electrons and holes, respectively, and $\alpha_n$ and $\alpha_p$ are the impact ionization rates for electrons and holes, which are defined that the number of electronic-hole pairs generated due to collision ionization by an electron or hole in a unit length.

For the SRH recombination, defect-assisted tunneling recombination (TAT) is also considered in it:

$$R_{\text{SRH}} = \frac{p n - n_i}{1 + \Gamma_p} \left[ \frac{n + n_i \exp \left( \frac{E_i - E_n}{k_B T} \right)}{1 + \Gamma_p} \right] + \frac{p + n_i \exp \left( \frac{E_i - E_p}{k_B T} \right)}{1 + \Gamma_n}$$

(3)
where $R_{SRH}$ is Shockley–Read–Hall recombination rate, $p$ and $n$ are hole and electron concentration, $n_i$ is intrinsic carrier concentration, $\tau_n$ and $\tau_p$ is life time for electrons and holes, $k_b$ is Boltzmann’s constant, $T$ is the Kelvin temperature, $E_d$ and $E_i$ are defect energy level and intrinsic energy level respectively. $\Gamma_{n,p}$ is the field enhancement coefficient obtained from Hurkx model (Hurkx et al. 1992).

The photogenerated carrier rate $G_{opt}$ of the absorption layer from the optical simulation is incorporated to obtain the photocurrent of the MIM-APD. Through the combination of optical and electrical simulation, the optoelectronic coupling effect between the MIM microcavity and the APD can be directly expressed, which is more conducive to the design and optimization of the device. In this paper, 2D simulation is used to save time and computing memory.

### 3 Results and discussion

The transmission spectrum of the MIM microcavity is shown in Fig. 2a. The peak transmission located at 1.55 μm reaches 60%. Figure 2b and Fig. 2c show the electric field distribution through the MIM microcavity. After passing through the top Au grating layer, the incident TM light is transformed into the surface plasmon polariton (SPP) wave, which is $y$-direction polarized and propagates along $\pm x$. The SPP wave is perfectly confined in the SiO$_2$ insulator cavity. Through the output slots in the bottom grating layer, the SPP wave in the cavity is transformed into the TM light again. However,
the output light from the MIM microcavity has a small divergence angle. Therefore, the
distance between the MIM’s output holes and the APD’s absorption layer directly deter-
mines the photoelectric coupling effect.

The Au strip structure shows obvious polarization characteristics, which is sensitive
to the incident angle, as shown in Fig. 2d. If the strip structure is changed into a ring
structure, the polarization independence can be better improved. But the angle of inci-
dent light will cause a little bit shift of the peak wavelength.

Figure 3a shows a cross section diagram of the MIM-APD. The distance from the
bottom grating layer of the MIM cavity to the APD absorption layer is denoted as $T$,
which includes the $p^+$ InP layer, the InP multiplication layer, the InP charge layer and
the InGaAsP layer with tens of nanometers. Because the thickness of InGaAsP is very
thin, we consider it together with InGaAs layer. In order to stabilize the performance of
the APD, the thicknesses of the multiplier layer, charge layer and the InGaAs absorption
layer are kept as 0.8 μm, 0.1 μm, and 1.5 μm. Only the thickness of the $p^+$ layer is vari-
able. Figure 3b shows the energy flux density distribution of the light emitted from the
MIM microcavity, with $T$ varying from 1.0 to 3.5 μm. We can see that the output light is
mainly concentrated in the center, and gradually diverges to both sides with the increase
of $T$. This result means that in the design of the APD, in order to reduce the active area
(denoted as $D$), it is necessary to make the absorption layer as close to the MIM cavity
as possible, so that most of the light can be fully absorbed in the InGaAs absorption
layer.

Figure 4 shows the photocurrent to the dark current ratio (here we call it SNR) at
the bias voltage of 30 V. It can be seen that SNR decreases with the increase of $D$, and
tends to be stable when $D$ approaches 6 μm. For smaller $D$, the rapid decrease of SNR
is due to the fact that the growth rate of the photocurrent is slower than that of the dark
current, which is proportional to $D$. But when $D$ is greater than 6 μm, the two growth
rates tend to be balanced, which means an efficient photoelectric conversion efficiency.
Considering the feasibility of the actual device’s fabrication, this structure with $T$ of 1.0
μm and $D$ of 6 μm is optimized for MIM-APD, and is used in the following simulation.
We compare the performance of the optimized MIM-APD with the traditional APD, with the same $T$ as 1.0 μm. Figure 5a shows the simulated two-dimensional structure of the MIM-APD with $D = 6$ μm and the total length of the MIM cavity is 21 μm, Fig. 5b shows the MIM free traditional APD with $D = 21$ μm, and the surface is antireflection coated with a transmittance of 94.8%. Figure 5c shows the simulated I–V curves of the two APDs. When the bias voltage is 30 V, the photocurrents of the traditional APD and the MIM-APD are 9.81 nA and 6.57 nA respectively, and the dark currents are 8.69 pA and 2.54 pA. The decrease of photocurrent in the MIM-APD is mainly due to 60% transmittance of the MIM cavity, as indicated in Fig. 2. In this paper, due to the two-dimensional simulation, the dark current is only proportional to the width of the active region, but for the practical devices, which is proportional to the area of the active region. Therefore, with the decrease of $D$, the dark current of the MIM-APD will decrease in a square multiple. The SNR of the two APDs is shown in Fig. 5d. The SNR of the MIM-APD is twice as that of the traditional APD. At the bias voltage of 28.9 V, the SNRs are 5300 and 2270, respectively.

In order to analyze the 3 dB bandwidth of the APD near the Geiger mode, we performed a transient simulation with a multiplication gain of 85. The calculated 3-dB bandwidth is shown in Fig. 5e. The 3-dB bandwidths of the two APDs are 5.8 GHz and 3.9 GHz, respectively. The 3-dB bandwidth of the MIM-APD is 49% higher than that of the traditional APD, which shows that a smaller $D$ will make a higher 3-dB bandwidth.

When the MIM microcavity is applied to an APD array, the optical crosstalk is analyzed. The whole length of the MIM cavity is 21 μm, the active width of the APD is $D = 6$ μm, and the distance between the adjacent MIM cavities is 0.5 μm. The light is incident on the first pixel, we observe the optical response of the adjacent two pixels, as shown in Fig. 6a. It shows the light electric field $|E|$ distribution of the three pixels. We can see that the output light from the MIM cavity is mainly concentrated in the first pixel. If an optical transmission monitor is placed on the periphery of the second pixel (around the red frame of crosstalk P1), the optical power is only 0.00138% of the incident light. Figure 6c shows the I–V curves of the three pixels. A small crosstalk current is found at the punchthrough voltage 28.9 V in the second pixel, which is 2.19 pA. Compared with the photocurrent of the first pixel at the same bias voltage, the crosstalk current is only 0.0353% of the photocurrent. The current of the third pixel almost coincides with the dark current. The results show that the crosstalk effect of MIM-APD is almost negligible.
4 Summary

The optoelectronic coupling effect of the MIM microcavity and the APD is optimized by the method of the photoelectric joint simulation. Considering a certain divergence angle of the output light from the MIM cavity, the active width of the APD is designed as 6 μm and the distance from the MIM bottom layer to the absorption layer is designed as 1 μm. Compared with the traditional APD, the SNR of the MIM-APD is twice that of the traditional one, and the 3 dB bandwidth is increased by 49%. Through optical crosstalk simulation, it's found that the optical crosstalk of the APD array integrated with MIM microcavities is very low, and only the first adjacent pixel has a crosstalk current, which accounts for...
0.0353% of the photocurrent. The MIM-APD provides an opportunity for the development of devices with higher sensitivity and higher bandwidth, and also provides a reliable idea for the development of large array APDs with low crosstalk and small pixels.

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