Optimization of top coupling grating for mid-wave quantum well infrared photodetector

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The relative coupling efficiency of top two-dimensional metal coupling grating for mid-wave quantum well infrared photodetector is calculated by finite difference time domain algorithms. The relative coupling efficiency with respect to the grating parameters, such as grating period, duty ratio, and grating depth, is computed. The calculated results show that the relative coupling efficiency will reach the largest value for the 4.1 μm incident infrared light when taking grating period as 1.3 μm, duty ratio as 0.75, grating depth as 0.4 μm.

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In the last two decades, owing to progress in crystal growth, photolithography, and semiconductor etching, there has been significant progress in the quantum well infrared photodetector (QWIP) technology leading to large format focal plane arrays[1−6]. According to the selection rule of quantum well inter-subband transition, the optical coupling structures must be incorporated to enable QWIP absorption of normally incident light. By using the common optical coupling structure, such as two-dimensional (2D) metal grating and corrugated grating, the GaAs based 1 024×1 024 long wavelength (LW), 1 024×1 024 mid-wavelength (MW), and 1 024×1 024 dual-band QWIP FPAs have been demonstrated[7−9]. But the GaAs based QWIP is not attractive for many applications because of its lower quantum efficiency and lower coupling efficiency of top metal grating. In addition, due to the better atmospheric transmission in comparison with the $4.3-5$ μm and the $8-14$ μm windows, detection in the $3-4.2$ μm window is also very interesting[10−12].

In this letter, the 2D metal coupling grating for mid-wavelength QWIP was studied by finite difference time domain method (FDTD) in order to increase its coupling efficiency. The relative coupling efficiencies with different grating parameters were compared and the optimal parameters of grating, such as period, duty ratio and grating depth, have been obtained.

The QWIP device structure simulated is illustrated in Fig. 1. The structure is composed of GaAs substrate, n type GaAs contact layer, typical GaAs/AlGaAs multiple quantum well (MQW) layer, 2D metal coupling grating, and gold reflective layer. For convenience, the growth direction of MQW layer is set to z coordinate, the bottom of MQW is set to z=0 and the device plane is set to x-y plane, the center point of x-y plane is set to x=0, y=0, which is shown in Fig. 1. Supposing the light incident from the GaAs substrate, the coupling efficieny of x-y plane at z point can be expressed as[13]

$$\eta(z)=\frac{\iint E_z^2(x,y,z)\mathrm{d}x\mathrm{d}y}{\iint E_{\text{in}}^2(x,y,z)\mathrm{d}x\mathrm{d}y}, \qquad (1)$$

where E_z is the z direction electric component in x-y plane at z point, z is the distance from the bottom of MQW layer to monitoring plane, E_{in} is the incident electric components E_x and E_z.

We analysis the coupling efficiency of top coupling grating by FDTD. One attraction is that because of the limitation of computer, all the MQW region was not selected to integration. Accordingly, a reasonable integral area is selected and fixed, so the relative coupling efficiency is obtained. We select the x-y planes at z=0.4, 0.6, 0.8, 1.0, 1.2 μm and the x, y integration area is 2.85×2.85 (μm) in the center of x-y plane.

Firstly, set the grating parameters as grating period P=1.1 μm, duty ratio d/P = 0.5, grating depth h = 0.312 5 μm, and the input light as TE mode (E_z = 0), the E_z field in MQW layer is calculated by FDTD. The E_z distribution at λ = 4.1 μm is illustrated in Fig. 2.

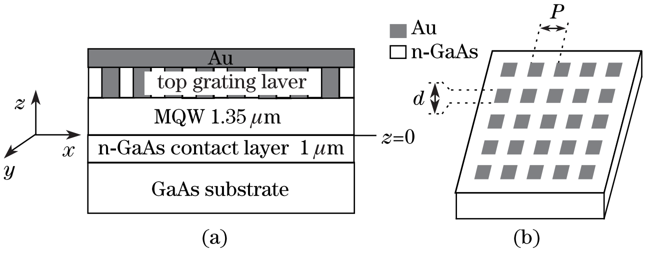

Fig. 1. QWIP structure. (a) Device structure and coordinate direction; (b) structure of 2D coupling grating.

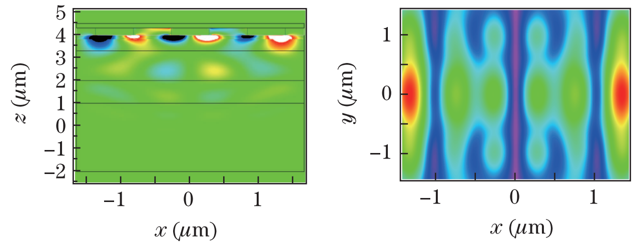

Fig. 2. E_z distribution for λ=4.1 μm incident light. (a) E_z distribution in x-z plane at y=0.01 μm; (b) E_z distribution in x-y plane at z=1.2 μm.

It shows that the electric field polarization direction is changed obviously by the coupling grating. Further conclusion can be obtained from Fig. 2(a) that the closer to the grating bottom, the stronger the E_z electric field.

Secondly, in order to obtain the more accurate analysis, the relative coupling efficiency of grating is calculated by Eq. (1) in the fixed integral area which is described above. Figure 3 shows the relative coupling efficiency with respect to the grating period. It can be seen that the grating coupling efficiency reaches the maximum when the grating period is 1.3 μm. This result is in agreement with the grating equation. And this result proves that the model and method in this letter are correct.

And then, by taking the grating period as P=1.3 μm, the relative coupling efficiency is calculated when the duty ratio d/P is changed. The calculated results are shown in Fig. 4. It shows that the peak value of relative coupling efficiency is achieved when the duty ratio is taken as 0.75.

Furtherly, by taking duty ratio as $d/P = 0.75$, the relative coupling efficiency is computed with respect to the grating depth. The calculated results are shown in Fig. 5. It can be concluded that the largest relative coupling efficiency will be reached when the grating depth is 0.4 μm.

Finally, the optimum parameters of top coupling grating for 4.1 μm input infrared light is obtained, which is illustrated as grating period P=1.3 μm, duty ratio $d/P = 0.75$, grating depth 0.4 μm.

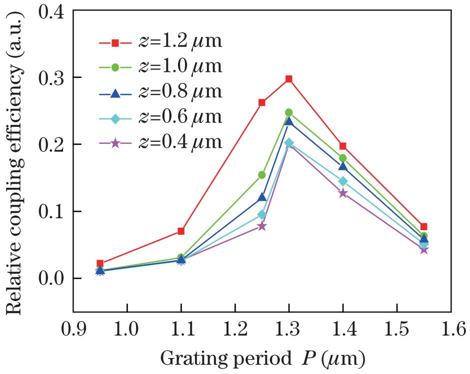

Fig. 3. Relative coupling efficiency with respect to the grating period.

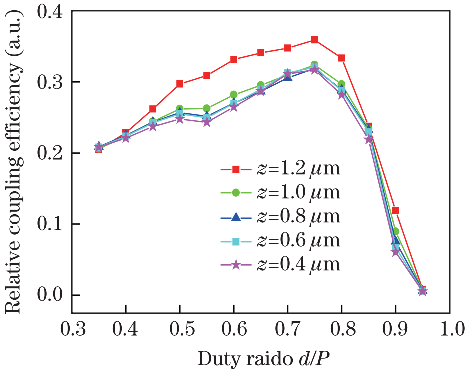

Fig. 4. Relative coupling efficiency with respect to the duty raido.

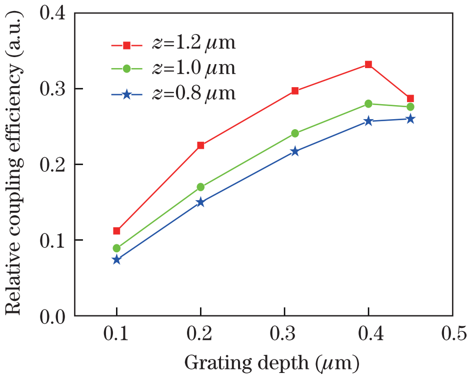

Fig. 5. Relative coupling efficiency with respect to the grating depth.

In conclusion, the relative coupling efficiency of top 2D metal coupling grating for mid-wave quantum well infrared photodetector is calculated by FDTD. The optimum parameters of top coupling grating are obtained by maximizing the coupling efficiency for different grating parameters. This work is beneficial to enhancing the performance of the mid wavelength QWIP focal plane array devices.

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