Design of a top mirror for the n-GaAs homojunction far-infrared/terahertz detectors

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The top mirror of the resonant cavity enhanced homojunction interfacial workfunction internal photoemission (HIWIP) far-infrared (FIR)/terahertz (THz) detector is investigated. Aiming at an existing half-optimized n-GaAs HIWIP FIR/THz detector, two designs of the top mirror are investigated to increase the quantum efficiency. The genuine or equivalent single layer is proved to be unqualified as the top mirror. A design based on the two-dimensional (2D) periodical reversed pyramidal structure of intrinsic GaAs is proposed as the top mirror. The resulted quantum efficiency can be as high as 29.0%. Some elementary thoughts and a tentative fabricating solution of this 2D periodical reversed pyramidal intrinsic GaAs top mirror are suggested. The designing ideas of this kind of top mirror may also be applied to other FIR/THz devices for reference. © *2010 American Institute of Physics*. [doi:10.1063/1.3491043]

I. INTRODUCTION

Far-infrared (FIR)/terahertz (THz) electromagnetic detection has received more and more attention nowadays, due to their potential applications in various areas, such as biomedical imaging, space astronomy, and spectroscopy.[1–4] In recent years, homojunction interfacial workfunction internal photoemission (HIWIP) FIR/THz semiconductor detectors, which have been demonstrated successfully in GaAs and Si,[5–10] attract significant attention. The unique feature of these detectors is that the cutoff wavelength can be tailorable, i.e., any cutoff wavelength, in principle, in FIR/THz radiation range can be developed as needed.[11] In addition, the advantages provided by the mature material technology for large scale focal plane arrays also make HIWIP detector a favorable alternative in FIR/THz applications. However, progress has been impeded by the limitation of relatively low quantum efficiency, which is a key parameter to characterize the performance of detectors.[12] Therefore, one of the primary goals of the HIWIP FIR/THz detector development is to increase the quantum efficiency as high as possible.

Generally, applying a resonant cavity to a detector is a common choice to increase the quantum efficiency. The structure of resonant cavity enhanced (RCE) detectors is simply formed by sandwiching detectors between a pair of mirrors. However, considering the technical challenge, it is more complex to design the mirrors for RCE HIWIP FIR/THz detectors due to the long wavelength and the free carrier absorption nature in FIR/THz radiation range, in comparison with the near-infrared and mid-infrared detectors.[12] Aiming at a given n-GaAs HIWIP FIR/THz detector, we once tried to increase the quantum efficiency by applying two kinds of bottom mirror (GaAs mirror and gold mirror).[13] The resulted quantum efficiency of the detector with gold bottom mirror is 18.8%, which is three times larger than the previous one without a bottom mirror. However, it still cannot meet the demand of practical use and need to be further improved. In terms of previous anticipation, an ideal top mirror matching with the bottom mirror could make the quantum efficiency reach as high as 29%, meeting the requirement of NASA's SIRTF program.[13,14] Though investigation of top mirror is urgently needed, not even a bit practical information (e.g., structure, material, etc.) about such an ideal top mirror was suggested and investigated up to now. In fact, there are indeed studies on the application of some kind of mirrors in FIR/THz radiation range.[15–17] However, to our knowledge, in addition to high reflection mirrors, researches on the top mirror that are designed for partially transmitting of RCE FIR/THz devices are still limited at present. It seems to be a big challenge to design a true resonant cavity for devices applied in FIR/THz radiation range because of the technical difficulty and the characteristic of long wavelength. Study on the design of top mirror is not only necessary for HIWIP FIR/THz detectors but also significant for other devices applied in FIR/THz radiation range.

Compared with the investigation on actual devices, it costs less time and money and is more convenient to optimize a device by simulation. And above all, it has been proved to be effective and accurate to simulate the performance of HIWIP FIR/THz detector in terms of the previous research.[18] In this paper, we will focus on discussing the top mirror based on the existing n-GaAs detector with gold bottom mirror by simulation. A design of top mirror for the RCE n-GaAs HIWIP detectors was proposed and its effect on the quantum efficiency is analyzed in detail. We first discuss the possibility of a single layer as a top mirror. Then a design of top mirror was suggested and the parameters were optimized by simulation. Finally, some elementary thoughts and suggestions on fabricating of such a top mirror are presented, as well as some concluding remarks and discussions.

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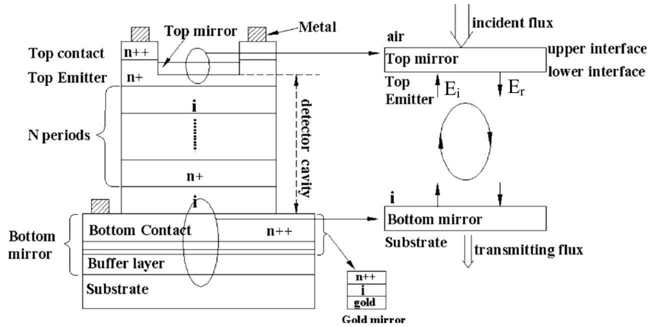

FIG. 1. The schematic structure of n-GaAs HIWIP FIR/THz detector after device processing. n^{++}, n^{+}, and i denote the contact layer, emitter layer, and intrinsic layer, respectively. The optical window is opened on the top. E_i and E_r are the internal incident and reflective electric field vector at the top mirror.

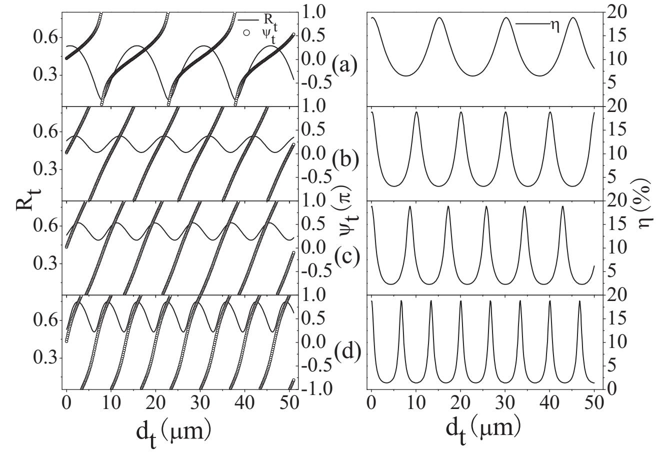

FIG. 2. The dependence of the reflectivity R_t, phase shift Ψ_t, and the quantum efficiency η on the thickness d_t of top mirror when the refractive index of a single layer (genuine or equivalent) top mirror is (a) 2.0, (b) 3.0, (c) 3.5, (d) 4.5, respectively.

II. RESULTS AND DISCUSSION

A. Discussion on a single layer as the top mirror

To acquire high quantum efficiency, the design of an ideal resonant cavity should consider the following aspects simultaneously: (1) the reflectivity of the bottom mirror of the resonant cavity should be as high as possible; (2) the choice of the top mirror should be appropriate to balance between the transmission for front side illumination of FIR/THz light and high internal reflection to ensure excellent resonant effect. That is to say that the reflectivity of the top mirror should match with the detector and the bottom mirror, too high or too low reflectivity would hamper the resultant effect; (3) the mirror itself should absorb as little energy as possible. In our previous work,[13] for an optimized n-GaAs HIWIP detector main structure, a thin gold layer has been suggested as a bottom mirror. The reflectivity of such a bottom mirror is 0.92, which is the highest reflectivity of the bottom mirror of HIWIP FIR/THz detector so far. Therefore, further investigation to improve the quantum efficiency of this n-GaAs HIWIP detector consisting of the optimized main structure with gold bottom mirror (we call it "the half-optimized detector" for short in this paper) should concentrate on the second aspect, i.e., proper selection of the top mirror. Previous research shows when the amplitude reflectivity R_t and phase shift Ψ_t of top mirror for the half-optimized detector are around 0.8 and zero, respectively, the quantum efficiency would be increased significantly and could be as high as 29.0%.[13] Therefore, the main purpose of this paper is to design a top mirror approaching such matched reflectivity and phase shift by simulation, based on the half-optimized detector. In fact, the analysis method about the top mirror for all HIWIP FIR/THz detectors is quite similar, only with some modifications. The designing ideas may also be applied to other FIR/THz devices for reference.

The schematic structure of the RCE detector after device processing is illustrated in Fig. 1. It mainly consists of N periods of heavily doped emitter layers and intrinsic layers, which is sandwiched between the top mirror and the bottom gold mirror. By being reflected between the top and bottom mirrors, the incident FIR/THz light travel through the absorbing area repeatedly (depicted in Fig. 1), forming a resonant effect. The amplitude reflectivity of top mirror is defined as $R_t=|E_r/E_i|$ and the corresponding phase shift is defined as $\Psi_t=\arg(E_r/E_i)$ (E_i and E_r are the internal incident and reflective electric field vector at the lower interface of top mirror, depicted in Fig. 1). According to the detection mechanism of HIWIP detectors,[13] the quantum efficiency η should be the product of the photon absorption probability in the detector cavity A, the efficiency that internal photoemission of photoexcited carriers across the junction barrier η_b, and barrier collection efficiency η_c, giving the formula $\eta = \mathrm{A}\eta_b\eta_c$. The photon absorption probability A of the multilayer structure is calculated by the Fresnel matrix approach, which presents techniques for the calculation of complex reflectivity and/or absorption of multilayer medium.[19,20] All the related parameters used in calculation can be found in Ref. 13. To compare with the previous results, one simplification is made that the light is normally incident without considering any light polarization effects and all the simulation is calculated at $\lambda=60\ \mu$m, if not pointed out specially.

It is known that, under the Fresnel matrix approach, some multilayer structure (for example, some kind of the symmetrical structure) can be equivalent to a single layer with a certain refractive index n_t and thickness d_t, which provides the amplitude reflectivity R_t and phase shift ψ_t. Based on such a reason, it is natural to start with a single layer as the top mirror for convenience. According to the condition (3) mentioned above, the top mirror is assumed to be nonabsorbing medium (it is approximately reasonable if intrinsic semiconductor is applied). Considering the possibility of practical fabrication, proper thickness of the top mirror is restricted to less than 50 μm. The reflectivity R_t and phase shift ψ_t, as well as the quantum efficiency η under different d_t and n_t when the single layer top mirror is applied to the half-optimized detector are necessary to be understood. It is found that the main features are similar, i.e., R_t, ψ_t, and η change periodically with d_t at different n_t. Therefore, in Fig. 2, we only present the dependence of R_t, ψ_t, and η on d_t, when n_t is 2.0, 3.0, 3.5, 4.5 for demonstration. It is noted that the average R_t increases with the increase in n_t. When n_t is smaller than the refractive index of the top emitter (3.2 +0.3i at λ=60 μm), e.g., n_t=2.0, 3.0, the top mirror only serves as a refractive index transitional layer from air to the top emitter layer, resulting in the peak value of R_t merely close to the reflectivity (0.53) at the native interface between air and the top emitter which corresponds to the case without the additional top mirror. Such low reflectivity cannot provide ideal resonant effect at all, leading to the low quantum efficiency. This kind of top mirror is obviously meaningless. In contrast, when n_t is larger than the refractive index of the top emitter layer (e.g., n_t=3.5 and 4.5), the peak value of R_t increase significantly. However, the resonant phase shift (i.e., ψ_t corresponding to the peak value of R_t) is then far away from the expected phase shift (near zero). This can be understood in terms of the light superposition principle. The peak value of R_t happens when the resultant reflected beam is the constructive superposition, which means different reflected rays at the lower interface of top mirror are in phase. The resultant resonant phase shift ψ_t is equal to the phase shift in the reflection at the lower interface. When n_t is smaller than the refractive index of the top emitter, reflection occurs from optically denser layer to optically thinner layer and no half-wave loss happens, making the resonant ψ_t staying around zero. In contrast, when n_t is larger than the refractive index of the top emitter, reflection at the lower interface occurs from optically thinner layer to optically denser layer and half-wave loss happens, making the resonant ψ_t being away from zero and close to π. Though the resonant ψ_t is not precisely to be zero or π due to influence of complex refractive index's imaginary part of the top emitter, the qualitative analysis above is correct. That is to say, if a single layer is employed as the top mirror, proper reflectivity, and the expected phase shift cannot be obtained simultaneously, leading to no improvement of the quantum efficiency. Therefore, a single layer cannot be used as a perfect top mirror.

B. Discussion on two-dimensional (2D) periodical reversed pyramidal structure as the top mirror

Now that a genuine or equivalent single layer as the top mirror has been proved to be unqualified, we turn to a complex structure that cannot be equivalent to a single layer. According to the above analysis, to obtain high quantum efficiency proper reflectivity and the desired phase shift should be satisfied simultaneously. However, it seems to be in a dilemma, because for one hand the top mirror should have large refractive index difference from both sides medium to ensure high reflectivity; on the other hand at the lower interface of the top mirror reflection should occur from optically denser medium to optically thinner medium to satisfy the condition of desired phase shift. Therefore, any design that could solve this contradiction would be qualified no matter what the material and structure of the top mirror is. It is known that some kind of 2D periodical structure, such as 2D periodical pyramidal structure which is often used as antireflection layer of substrate[21] or solar cells,[22,23] may lead to the refractive index vary continuously from air to the medium itself. This makes it possible to solve the above contradiction if such a 2D periodical structure is reversed placed at the top of the detector. In the following, we discuss the 2D periodical reversed pyramidal structure of intrinsic GaAs as the top mirror.

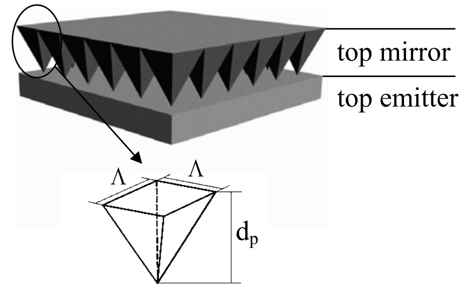

FIG. 3. The schematic structure of the 2D periodical reversed pyramidal intrinsic GaAs top mirror. Λ is the length of period and d_p is the height of pyramid.

Figure 3 illustrates the schematic structure of the reversed pyramidal intrinsic GaAs top mirror. Λ is the length of period and d_p is the height of pyramid. Due to the application of intrinsic GaAs, the absorption of the top mirror itself could be ignored. This structure can be regarded as the composition of many extremely thin layers whose effective refractive index is dependent on the volume ratio of reversed pyramid material and air. We assume that the reversed pyramidal structure is divided into M layers along the growth direction. Thus the thickness of each layer is equal to d_p/M. It is easy to understand that larger M must lead to more precise results. However, when M is large enough, e.g., M >500 in the case of d_p less than 50 μm, it may not affect the precision of calculation any more. In calculation, we uniformly divide this structure into 5000 layers, i.e., M=5000, regardless of the value of d_p. The effective refractive index of each layer is $n_{eff}=\sqrt{f\times n_{\mathrm{GaAs}}^2+(1-f)\times n_{air}^2}$, where f is the filling factor (volume fraction) of intrinsic GaAs in each thin layer and n_{GaAs}=3.7.[21] With the thickness and effective refractive index of each thin layer, the calculation can also be performed by Fresnel matrix method. It is clear that the refractive index of the top mirror changes continuously from the upper extremely thin layers with large filling factor ($n_{eff}\approx n_{\mathrm{GaAs}}$) to the lower extremely thin layers with small filling factor ($n_{eff}\approx n_{air}$). In calculation, the 2D periodical structure is treated as a zeroth-diffraction-order grating, which is appropriate when $\Lambda\leq\lambda/n_{\mathrm{GaAs}}$ (normal incidence), with λ incident wavelength in vacuum.[21,24] As far as the investigated detector is concerned, Λ should be less than 16.2 μm. In the following, we assume Λ to be 10 μm. It is noted that the unique feature of this kind of top mirror is that it possesses two interfaces, i.e., the upper and lower interfaces, both of which offer abrupt variation in refractive index with almost the same abruptness. The upper interface separates the air and the extremely thin layer with the very large GaAs filling factor ($n_{eff}\approx n_{\mathrm{GaAs}}$). And the lower interface separates the extremely thin layer with very small GaAs filling factor ($n_{eff}\approx n_{air}$) and the top emitter layer. Obviously, reflection at the lower interface of top mirror occurs from optically denser layer to optically thinner layer.

The dependence of the reflectivity R_t and phase shift ψ_t on the height d_p of such a top mirror is investigated in Fig. 4.

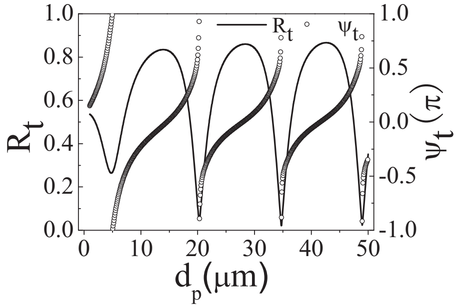

FIG. 4. The dependence of the reflectivity R_t and phase shift Ψ_t on the thickness d_p of the 2D periodical reversed pyramidal intrinsic GaAs top mirror.

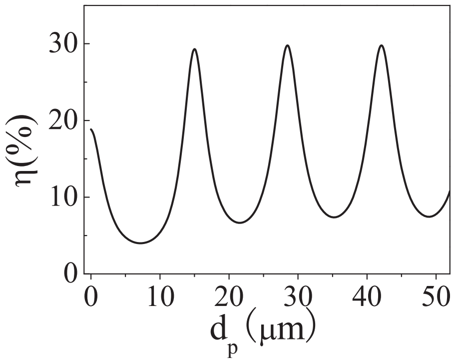

FIG. 5. The dependence of the quantum efficiency η on the thickness d_p of 2D periodical reversed pyramidal intrinsic GaAs top mirror.

It is clear that R_t and ψ_t also change periodically (though not strictly) with d_p when d_p is larger than 13 μm. This is because: from the lower interface to the upper interface the difference of effective refractive index is fixed, increasing d_p means the refractive index changes more and more gently, that is to say the top mirror becomes more uniform in the unit depth along the growth direction. Therefore, at large d_p the reflection resulted from the inner part of such a top mirror is much smaller than that of the upper and lower interfaces with abruptly changing refractive index due to its feature of continually changing refractive index. The increase in d_p mainly affects the phase shift ψ_t. So when d_p is larger than 13 μm, it plays a similar role of d_t in the case of a single layer discussed in Fig. 2 where R_t and ψ_t change strictly periodically with d_t. It is obvious to see in Fig. 4 that the peak values of R_t is around 0.8, and the corresponding resonant phase shift ψ_t is near zero, which approaches the desired reflectivity and phase shift. The reasons why such a 2D periodical reversed pyramidal top mirror can realize the combination of R_t of about 0.8 and ψ_t close to zero, while a single layer top mirror was proved unable, can be explained in a simple way. The reflection by the lower interface alone has already provided R_t of 0.53. Another upper interface where the refractive index also changes abruptly (with almost the same abruptness) may further increase resultant reflection. By changing the thickness d_p, constructive superposition condition can be satisfied, which makes the reflectivity be enhanced once again by the reflection at the upper interface, leading to a rather high peak value of R_t. In addition, reflection at the lower interface is from optically denser layer to optically thinner layer, so no half-wave loss happens, resulting in resonant phase shift ψ_t approaching zero. Whereas, in the case of a single layer top mirror, either the upper and lower interfaces can not provide abruptly changing refractive index with enough abruptness (low refractive index of n_t), leading to low reflectivity, or half-wave loss occurs (high refractive index of n_t), resulting in the resonant phase shift ψ_t far from the desired one. In a word, no matter what the structure of the top mirror is, it should not only possesses interfaces where the refractive index change abruptly enough to obtain a high peak value of reflectivity R_t but also make sure that reflection occurs at the lower interface is from optically denser medium to optically thinner medium to ensure the resonant ψ_t close to zero. Figure 5 demonstrates the dependence of quantum efficiency η on d_p after the 2D periodical reversed pyramidal intrinsic GaAs top mirror is applied to the half-optimized detector. It can be clearly seen that η changes periodically with d_p and reaches its peak values at 15, 28, 42 μm and so on (where the peak values of R_t and resonant ψ_t happen). From the view point of fabrication simplicity, d_p is considered to be 15 μm and the corresponding η is as high as 29.0%. Further calculation shows when η is 29.0% the power reflectivity of the whole detector drops to 1.6%, indicating a significant effect of anti-reflection of the top mirror.

To know the performance over broad wavelength coverage of this fully optimized RCE detector (the half-optimized detector with the 2D periodical reversed pyramidal top mirror when d_p is equal to 15 μm), the yielded quantum efficiency η as a function of wavelength is calculated. Figure 6 shows the dependence of η on incident wavelength of this fully optimized RCE detector as well as the half-optimized detector. After the application of reversed pyramidal top mirror, η shows an approximately symmetrical distribution centered at 60 μm over a wide radiation range, showing an excellent resonant effect. Though the quantum efficiency η is enhanced significantly near 60 μm, the bandwidth is narrowed. Its full width at half maximum is only about 5 μm, which is less than that of the half-optimized detector in our previous work (about 22 μm). This means higher quantum efficiency will sacrifice broad bandwidth of the detector to some extent. Though such a top mirror shows no sign of

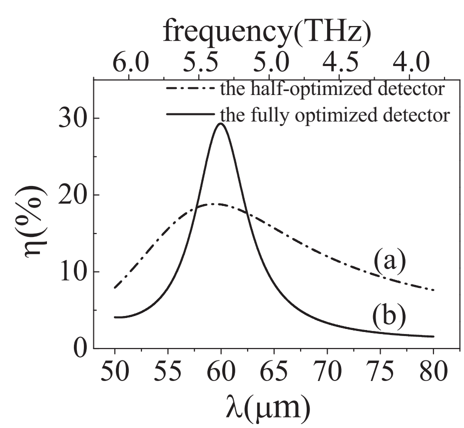

FIG. 6. The dependence of the quantum efficiency η on the wavelength λ for (a) the half-optimized detector and (b) the fully optimized detector.

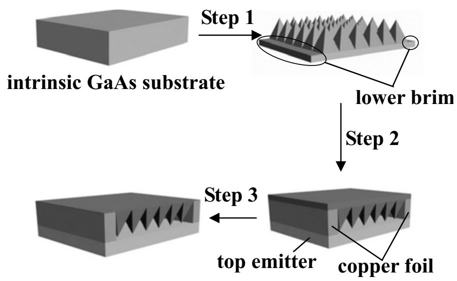

FIG. 7. The imaginable processing procedure of three steps to realize the 2D periodical reversed pyramidal intrinsic GaAs top mirror. Step1, the 2D periodical upright pyramidal structure on an intrinsic GaAs substrate (with lower brim) is fabricated. Step 2, it is mounted upside down on the top emitter by using copper foil at the border to support. Step 3, the unwanted part of this substrate is etched to reduce the topmost surface to an appropriate level both to fit to design and to maintain enough mechanical strength.

improvement of the net response, it should be noted on the other hand that such kind of 2D periodical reversed pyramidal top mirror can be easily designed to match different detect wavelength as need.

C. Tentative solution to 2D periodical reversed pyramidal top mirror

It is known that 2D periodical upright silicon pyramidal structure can be realized by crystallographic wet etching method.[21] Researches show that GaAs upright pyramidal structure can also be obtained.[25] Therefore, it provides the possibility to realize the proposed GaAs reversed pyramidal top mirror. Here we just conceive a tentative solution to the realization of such a top mirror. Figure 7 illustrates the imaginable processing procedure of three steps. First, the 2D periodical upright pyramidal structure on an intrinsic GaAs substrate (with lower brim) is fabricated. Then, it is mounted upside down on the top emitter by using copper foil at the border to support, just like the method in Ref. 26. The thickness of the copper foil is set rather precisely to enable the tips of the pyramids touch the surface of the top emitter exactly. Finally, the unwanted part of this substrate is etched to reduce the topmost surface to an appropriate level both to fit to design and to maintain enough mechanical strength. The 2D periodical reversed pyramidal intrinsic GaAs top mirror could be thereby finished. If the 2D periodical reversed pyramidal top mirror cannot be strictly fabricated, a more realistic 2D sparse periodical reversed quadrangular frustum pyramid structure may also do well as top mirror. Figure 8 demonstrates such a structure, Λ is the period

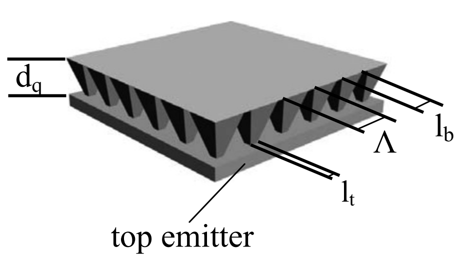

FIG. 8. The schematic structure of the 2D sparse periodical reversed quadrangular frustum pyramid top mirror. Λ is the period length, d_q is the height of quadrangular frustum pyramid, l_b is the length of the bottom square of quadrangular frustum pyramid, and l_t is the length of the top square of quadrangular frustum pyramid.

length, d_q is the height of quadrangular frustum pyramid, l_b is the length of bottom square of quadrangular frustum pyramid, and l_t is the length of top square of quadrangular frustum pyramid. According to calculation, when Λ, d_q, l_b, l_t are equal to 10 μm, 15 μm, 7.8 μm, 2 μm, respectively, the quantum efficiency of the corresponding RCE detector is 27.3%, which is also satisfactory. The idea about the design of top mirror may also be applied to other FIR/THz devices for reference.

III. CONCLUSION

In this paper, the top mirror is investigated based on an existing half-optimized n-GaAs HIWIP FIR/THz detector. A genuine or equivalent single layer is first discussed and proved to be unqualified. It is found that an ideal top mirror is expected to have comparatively high reflectivity and a desired phase shift approaching zero. This requires the top mirror should possess interfaces where the refractive index changes abruptly. At the same time, reflection at the lower interface should occur from optically denser layer to optically thinner layer. Accordingly, we proposed a 2D periodical reversed pyramidal intrinsic GaAs as the top mirror. The highest quantum efficiency can be as high as 29%, which meets the practical requirements. However, the fully optimized detector acquires higher quantum efficiency by sacrificing broad bandwidth of the detector to some extent. Finally, a tentative solution to fabricate such a 2D periodical reversed pyramidal structure is suggested. The idea about the design of top mirror may also be applied to other FIR/THz detectors as reference.

ACKNOWLEDGMENTS

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