A Polarization-Dependent Normal Incident Quantum Cascade Detector Enhanced Via Metamaterial Resonators

Lei Wang, Shen-Qiang Zhai*, Feng-Jiao Wang, Jun-Qi Liu, Shu-Man Liu, Ning Zhuo, Chuan-Jin Zhang, Li-Jun Wang, Feng-Qi Liu* and Zhan-Guo Wang

Abstract

The design, fabrication, and characterization of a polarization-dependent normal incident quantum cascade detector coupled via complementary split-ring metamaterial resonators in the infrared regime are presented. The metamaterial structure is designed through three-dimensional finite-difference time-domain method and fabricated on the top metal contact, which forms a double-metal waveguide together with the metallic ground plane. With normal incidence, significant enhancements of photocurrent response are obtained at the metamaterial resonances compared with the 45° polished edge coupling device. The photocurrent response enhancements exhibit clearly polarization dependence, and the largest response enhancement factor of 165% is gained for the incident light polarized parallel to the split-ring gap.

Keywords: Infrared, Photodetectors, Polarization-selective devices, Metamaterials

Background

High-performance infrared photodetectors operating in the range of 3–14 μm are highly needed for a variety of applications, such as security surveillance, chemical sensing, and industrial process monitoring [1]. This has promoted increasing research interest in new materials and structures to improve detector performances, such as spectral sensitivity, leakage current level, and operating temperature. Therefore, semi-conductor intersubband photodetectors have been widely explored due to their capabilities of flexible energy-band tailoring and ultrahigh-speed operation [2, 3]. Inspired by the prototype of quantum cascade laser, a new type of semi-conductor intersubband detectors, quantum cascade detectors (QCDs) have been proposed and gained great progresses over the past decade [4]. Based on bound-to-bound intersubband transitions in a built-in asymmetric conduction band structure, QCDs share the advantages of operation wavelength designability, low noise photovoltaic operation mode and therefore room temperature operation capability over well-established detector types [5]. Thus, QCDs are largely free from the limit of the integration time due to capacitance saturation of the read-out circuit and very promising for thermal imaging. Moreover, the thermal load is strongly reduced which is of interest if the available cooling is limited, for example in spaceborne systems [6]. Up to the present, QCDs have covered a large wavelength range from the near-infrared to the terahertz region [7–14]. Many new structure designs have been presented to improved device performances, such as mini-band [12] and energy mini-steps [13] transport designs for very long wave detection and diagonal transition design [15, 16] for an improved overall performance. In addition, QCDs have prove their high-temperature operation capability [9, 17, 18], and exhibited their potential to be used for arrays in imaging applications [19].

However, QCDs suffer from the disadvantage of insensibility to normal incident light and low quantum efficiency, due to their intersubband transition principle [20]. Thus, many novel coupled structures have been applied to fulfill the intersubband transition selection rule and enhance quantum efficiency [21, 22]. Metamaterials
are man-made structures compositing of sub-wavelength periodically arranged metallic resonators that allow for three-dimensional control of light [23]. Utilization of resonant inclusions allows for the realization of stunning optical properties that cannot be found otherwise in nature, such as superlensing, negative refraction, or cloaking. These exotic properties strongly depend on the geometry of metamaterial molecules rather than their composition. Since they were theoretically proposed by Pendry et al. [24] and experimentally demonstrated by Smith et al. [25], metamaterials have attracted intensive research interest and extended to infrared region [26, 27] in recent years because of their wide applications in super lenses, slow light, data storage, optical switching, and so on. Another property of interest is that metamaterial resonators can excite a strong field enhancement in the near-field and be used as highly sub-wavelength electromagnetic cavities [28]. This property makes them the ideal candidates for coupling incoming light to a semiconductor medium and thus a promising method to enhance absorption in semi-conductor intersubband photodetectors. A. Benz et al. have innovatively applied a complementary split-ring resonator (CSRR) on a quantum-cascade-laser structure to enhanced photovoltaic detection in terahertz region and brought in inspiring results [29]. In this work, a similar structure is integrated on a quantum cascade detector in infrared region to enhance device response and, in further, the polarization selective enhancement property of the integrated device has been focused on. The metamaterial structure is designed through three-dimensional finite-difference time-domain (FDTD) method and directly fabricated into the top metal contact, which forms a double-metal waveguide together with the metallic ground plane. For one thing, the metamaterial layer will transfer the energy of the normal incident light into metamaterial resonant modes, which will be confined in the detector active region by the double-metal waveguide, as the same in Ref. 28. For another, the integrated device is expected to exhibit clearly polarization-dependent property due to the asymmetry of the metamaterial resonators. With normal incidence, significant enhancements of photocurrent response are obtained at the metamaterial resonances compared with the 45° edge facet coupling device. The photocurrent response enhancements exhibit clearly polarization dependence, and the largest response enhancement factor of 165% is gained for the incident light polarized parallel to the split-ring gap.

**Methods**

The quantum cascade detector used in this device was grown on a semi-insulating InP substrate by molecular beam epitaxy and designed to operate at a wavelength of $10.5 \mu m$. The quantum cascade detector structure of one period is demonstrated in the inset of Fig. 1b in detail. The structure is a normal design, which is not well-designed for coupling with the metamaterial structure. The integrated device structure and the basic building
block of the metamaterial are described schematically in Fig. 1. A 30-period chirped InGaAs/InAlAs superlattice (SL) active region and two Si-doped InGaAs($5 \times 10^{17}$ cm$^{-3}$) contact layers of 500 and 200 nm are sandwiched between an upper Au metamaterial layer and a bottom Au reflection layer whose thicknesses are both 100 nm. Thus, a double-metal waveguide structure is constituted to ensure a high overlap between the active detector region and the resonant mode excited by the metamaterial. Each building block of the metamaterial consists of a CSRR, which is directly fabricated into the top metal contact layer. Figure 1b also defines the coordinate system and shows the direction of the fundamental axes, which will be used throughout this work.

The metamaterial properties, such as positions and line widths of the resonances, highly depend on the shape and size of the metallic resonators and can be fully controlled by the geometry of the resonant elements. In this work, higher order resonant modes of a complementary split-ring metamaterial are excited to interact with the intersubband transitions in the quantum cascade detector's active origin. Three-dimensional FDTD simulations are performed for the structure design. Due to the Au film on the back, the structure does not allow light transmission, and therefore, its reflectance spectra is studied to characterize the metamaterial properties. The dips in the reflectance spectra correspond to the high metamaterial absorption and thus are the metamaterial resonances. According to the response spectrum obtained from the 45° edge facet coupling device, the dimensions of the metamaterial building block are determined and illustrated in the inset of Fig. 2. Due to the asymmetry in $x$–$y$ plane, the CSRRs will have different resonate properties for the incoming light with different polarized directions. Figure 2 shows the simulated reflectance spectra for two polarization incident light, along with the response spectrum of the origin quantum cascade detector. Resonance wavelengths of 10.7 and 10.3 $\mu$m are gained for $E_x$ and $E_y$ polarization incident light, respectively, by geometric scaling of the CSRRs to overlap with the detector's origin response spectrum with peak wavelength of 10.5 $\mu$m. In addition, there is another resonance at 11.5 $\mu$m on the edge of the response spectrum for $E_x$ polarization, which will have similar coupled property as the resonance at 10.7 $\mu$m. To reveal the coupling mechanism in the integrated device, the $E_z$ electric component distributions for the structure have been simulated and shown in Fig. 3. Figure 3a, b is $E_z$ electric component distribution in $x$–$y$ plane 200 nm below the metamaterial layer inside the semi-conductor for $E_x$ polarization incident light at 10.7 $\mu$m and $E_y$ polarization at 10.3 $\mu$m, respectively. The different spatial mode profiles for the $E_x$ and $E_y$ polarization incident light indicate that our device response goes beyond a simple grating coupler which would have the same response for both polarizations. Figure 3c, d is $E_z$ electric component distributions in $x$–$y$ and $y$–$z$ planes at $y = 0$ and $x = 0$ for $E_x$ polarization at 10.7 $\mu$m and for $E_y$ polarization at 10.3 $\mu$m, respectively. They demonstrate the existence of strong $E_z$ electric component through the whole active region confirming the significant confinements by the double-metal waveguide, which is vital for the device response enhancement.

The device processing starts with the upside down mounting of the epitaxy wafer. After the deposition of a Ti(20 nm)/Au(100 nm) layer on the top contact layer, the epitaxial layer is fixed onto an InP receptor substrate using Deamcheas electricity conductive adhesive. Therefore, the Ti/Au layer deposited on the top contact layer will act as the reflection layer and bottom electrode in the integrated device. Following that, lapping and selective wet chemical etching using hydrochloric acid were
performed to remove the original InP substrate and reach the InGaAs etch stop layer. Next, 300 × 400-μm² device mesas are defined by standard photolithography and wet etching process. The mesa depth was controlled to reach the bottom reflection Au layer. Then 300 × 300-μm² CSRRs metamaterial areas and 300 × 100-μm² top electrodes were fabricated on the top of device mesas using a combination of standard photolithography and metal lift-off process. The CSRRs layer has a depth of 100 nm. The device fabrication was then completed with chip cleavage and gold wire bonding. In the top picture of Fig. 4, a large area scanning electron microscopy (SEM) image of the metamaterial integrated device is shown. The top and bottom electrical contacts are indicated in the figure. In the bottom picture of Fig. 4, the zoom-in views of the CSRRs are shown. The SEM images indicate that the morphology of CSRRs is not so idealized, which is limited to the method through which the CSRRs are obtained. However, this method is simple and of low cost and more promising for practical applications, such as fabricating large-area focal plane arrays.

Results and Discussion

Once the device processing is completed, it is mounted onto a copper heat-sink and then fixed on the cold finger of a liquid nitrogen cryostat for device response measurements. The photocurrent response measurement was performed by Nicolet 6700 fourier transform infrared spectrometer (FTIR) with a KBr beam splitter and the internal glow-bar illumination. With the measured photocurrent spectrum, the responsivity spectrums were calibrated using a standard blackbody source. Figure 5a shows the photocurrent responsivity spectra of the metamaterial integrated devices. Also shown is that of a 45° edge facet coupling device made from the same QCD wafer as the reference. In this integrated device, the expected detector response is a convolution of the intersubband transitions in detector’s active region and the metamaterial resonances. Therefore, the response spectrum shape of the CSRRs coupled device is clearly modified compared to the 45° edge facet coupling device. In addition, significant response enhancements are obtained at metamaterial resonances for both polarizations, as is shown in the inset of Fig. 5a. And the largest response enhancement factor of 165% is gained at the wavelength of 11.5 μm for the $E_x$ polarization, which is far away from the peak response of the original device. This may be due to the low absorption for the original device, which will leave more electrons on the ground state for the metamaterial coupled absorption [30]. However, the response enhancement is not obtained in the whole response spectrum, which can be attributed to the narrow-banded property of the metamaterial resonances. In addition, at the peak response wavelength, incident light cannot coupled to the absorption region of the QCD structure efficiently through metamaterial resonances and thus the enhancement did not occur near the peak wavelength. Thus, in order to acquire enhancement through the whole response spectrum, metamaterial structures with broad-banded resonances should be designed and integrated to the detector [31]. Figure 5a also indicates that $E_x$ polarization have stronger enhancement than the $E_y$ polarization. To reveal the physical reason, the z-dependences of the total $|E_z|$ amplitude are calculated,
which is obtained by taking the areal integral
\[ F = \left| \int_0^d \int_0^d |E_z(x,y)| \, dx \, dy \right|, \]
for both \( E_x \) and \( E_y \) polarization incident light at metamaterial resonances of 10.7 and 10.3 μm, respectively, and is demonstrated in Fig. 5b. The results clearly demonstrated that the \(|E_z|\) areal integrals for \( E_x \) polarization incident light are larger than those for \( E_y \) polarization at different \( z \) positions. This indicates that \( E_x \) polarization incident light can excite \( E_z \) electric field more efficiently and thus bring in stronger response enhancement. Moreover, there are clear dips in \( F \) curves at the middle of the waveguide. Since the coupled modes are excited by the metamaterial layer and confined by the double-metal waveguide, it is expected that the \( E_z \) field is strongest just underneath the top metal and close to the bottom metal contact. Due to the serial structure of QCD active region, the device responsivity will be limited by the region with small \(|E_z|\) areal integral and thus low absorption. Therefore, further responsivity enhancement is in prospect by optimizing the position of absorption region in the waveguide, where the absorption region is layered at the positions with strongest \( E_z \) electric field. Another aspect that has to be considered is the ohmic losses due to the double-metal structure in the device, which will absolutely reduce the coupled energy in the detector and thus limit the response enhancement. In order to obtain exciting responsivity enhancement through metamaterial couple, special designed structures with low ohmic losses need to be investigated and employed in further study [32].

To further gain the polarization-dependent property of the device, device photocurrent has been measured with different polarization incident light. Figure 6 is the photocurrent curves changing with the azimuth positions of the polarizer. 0° polarization corresponds to polarization in \( x \) direction and 90° in \( y \) direction, as is shown in the inset in Fig. 6. The results unambiguously show that the spectral responses are highly dependent on the incidence light polarization, which indicates the feasibility to design polarization-selective detectors using metamaterial resonances. However, the \( E_x/E_y \) response ratio for this device is somewhat small. This can be due to the complex mutual effect of grating and metamaterial resonances, which is expected as the periodicity of the metamaterial is comparable to the effective wavelength inside the active region. In order to obtain high polarization discriminating detectors for practical application, such as polarimetric imaging, optimized metamaterial design should be implemented [33].
Furthermore, taking advantage of the unique properties of metamaterial, various metamaterial designs can be employed to implement multi-functional detector. For example, metamaterial structures with chirality can be applied to fabricate circular polarization discriminating detectors [34].

Conclusions
In conclusion, a polarization-dependent normal incident quantum cascade detector coupled via complementary split-ring metamaterial resonators has been demonstrated. The metamaterial structure is fabricated directly into the top metal contact and forms a double-metal waveguide together with the metallic ground plane. With normal incidence, significant enhancements of photocurrent response are obtained at the metamaterial resonances compared with the 45° edge facet coupling device. And the largest response enhancement factor of 165% is gained at the wavelength of 11.5 μm for the $E_x$ polarization. The response spectral also exhibits clearly polarization dependence, which outlines the advantages of metamaterial coupled design for polarization discriminating application. In further, taking advantage of the unique properties of metamaterial, many new IR detector functionalities can be implemented by designing suitable metamaterial structures, which presents a promising way for fabrication of high performance or special functional device for practical applications.

Abbreviations
CSRR: Complementary split-ring resonator; FDTD: Three-dimensional finite-difference time-domain; FTIR: Fourier transform infrared spectrometer; QCDs: Quantum cascade detectors; SEM: Scanning electron microscopy; SL: Superlattice

Acknowledgements
The authors would like to thank Ping Liang and Ying Hu for their help in device processing.

Funding
This work was supported by the National Natural Science Foundation of China (Grant Nos. 61504135, 61376051) and the National Basic Research Program of China (Grant No. 2013CB632804/02).

Authors' contributions
LW have provided this idea, designed the structure, doing most of the simulation and wrote part of the paper. S-QZ fabricated the device, performed the testing, and wrote part of the paper. F-JW performed part of the device measurement. J-QL and F-QL revised the paper and supervised the project. S-ML and LJ Wang gave some helpful discussions on the device measurement. NZ completed the MBE growth of the wafer. ZGW supervised the project. All authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

Received: 22 September 2016 Accepted: 21 November 2016 Published online: 01 December 2016

References
1. Rogalski A, Antoszewski J, Farah el.L (2009) Third-generation infrared photodetector arrays. J Appl Phys 105:091101
2. Levine BF (1993) Quantumwell infrared photodetectors. J Appl Phys 74:R1–R81
3. Liu HC, Jammeng L, Buchanan M, Wasilewls ZR (1996) High-frequency quantum- II infrared photodetectors measured by microwave-rectification technique. IEEE J Quantum Electron 32:1024–1028
4. Gendron L, Carras M, Huynh A, Ortiz V (2004) Quantum cascade photodetector. Appl Phys Lett 85:2824–2826
5. Giorgetta FR, Baumann E, Graf M, Yang Q, Manz C, Köhler K, Beere HE, Ritchie DA, Linfield E, Davies AG, Fedonyshyn Y, Jäckel H, Fischer M, Faist J, Hofstetter D (2009) Quantum cascade detectors. IEEE J Quantum Electron 45:1039–1052
6. Giorgetta FR, Baumann E, Théron R, Pellaton ML, Hofstetter D, Fischer M, Faist J (2008) Short wavelength 4 μm quantum cascade detector based on strain compensated InGaAs/InAlAs. Appl Phys Lett 92:121101

7. Vardi A, Bahar G, Guillot F, Bougerol C, Monroy E, Schacham SE, Tchernycheva M, Julien FH (2008) Near infrared quantum cascade detector in GaN/AlGaN/GaN heterostructures. Appl Phys Lett 92:011112

8. Giorgetta FR, Baumann E, Hofstetter D, Manz C, Yang Q, Köhler K, Graf M (2007) InGaAs/AlAsSb quantum cascade detectors operating in the near infrared. Appl Phys Lett 91:111115

9. Graf M, Hoyner N, Giovannini M, Faist J, Hofstetter D (2006) InP-based quantum cascade detectors in the mid-infrared. Appl Phys Lett 88:241118

10. Kong N, Liu JQ, Lu L, Liu FQ, Wang LJ, Wang ZG, Lu W (2010) A 10.7 μm InGaAs/InAlAs quantum cascade detector. Chin Phys Lett 27:128503

11. Buffaz A, Carras M, Doyennette L, Nadelcu A, Marcadet X, Berger V (2010) Quantum cascade detectors for very long wave infrared detection. Appl Phys Lett 96:172101

12. Giorgetta FR, Baumann E, Graf M, Ajili L, Hoyler N, Giovannini M, Faist J, Hofstetter D, Krotz P, Sonnenbarg G (2007) 16.5 μm quantum cascade detector using miniband transport. Appl Phys Lett 90:231111

13. Zhai SQ, Liu JQ, Wang XJ, Zhuo N, Liu FQ, Wang ZG, Liu XH, Li N, Lu W (2013) 19 μm quantum cascade infrared photodetectors. Appl Phys Lett 102:191120

14. Graf M, Scalari G, Hofstetter D, Faist J (2004) Terahertz range quantum well infrared photodetector. Appl Phys Lett 84:475–477

15. Reininger P, Schwarz B, Detz H, Farland DM, Zederbauer T, Andrews AM, Schrenk W, Baumgartner O, Kosina H, Strasser G (2014) Diagonal-transition quantum cascade detector. Appl Phys Lett 105:091108

16. Reininger P, Schwarz B, Gansch R, Detz H, MacFarland D, Zederbauer T, Andrews AM, Schrenk W, Strasser G (2015) Opt Express 23:6283–6291

17. Hinds S, Buchanan M, Dudek R, Hoffouz S, Lafraimboise S, Wasilewski Z, Liu HC (2011) Near-room-temperature mid-infrared quantum cascade photodetector. Adv Mater 23:5536–5539

18. Wang XJ, Liu JQ, Zhai SQ, Liu FQ, Wang ZG (2014) Room temperature quantum cascade detector operating at 4.3 μm. J Semicond 35:104009

19. Harrer A, Schwarz B, Schuler S, Reininger P, Wirthmüller A, Detz H, MacFarland D, Zederbauer T, Andrews AM, Rothermund M, Oppermann H, Schrenk W, Strasser G (2016) 4.3 μm quantum cascade detector in pixel configuration. Opt Express 24:17041–17049

20. Wang YC, Li SS (1994) Design of a two-dimensional square mesh metal grating coupler for a miniband transport GaAs quantum-well infrared photodetector. J Appl Phys 75:582–587

21. Zhai SQ, Liu JQ, Liu FQ, Wang ZG (2012) A normal incident quantum cascade detector enhanced by surface plasmons. Appl Phys Lett 100:181104

22. Reininger P, Schwarz B, Harrer A, Zederbauer T, Detz H, Andrews AM, Gansch R, Schrenk W, Strasser G (2013) Photonic crystal slab quantum cascade detector. Appl Phys Lett 103:241103

23. Chen T, Li S, Sun H (2012) Metamaterials application in sensing. Sensors 12:2742–2765

24. Pendry JB, Holden AJ, Robbins DJ, Stewart WI (1999) Magnetism from conductors and enhanced nonlinear phenomena. IEEE Trans Microw Theory Tech 47:2075–2084

25. Shelby RA, Smith DR, Schultz S (2001) Experimental verification of a negative index of refraction. Science 292:77–79

26. Dayal G, Ramakrishna SA (2014) Design of highly absorbing metamaterials for infrared frequencies. Opt Express 20:17503–17508

27. Liu XL, Starr T, Starr AF, Padilla WJ (2010) Infrared spatial and frequency selective metamaterial with near-unity absorbance. Phys Rev Lett 104:207403

28. Benz A, Campione S, Liu S, Montano I, Klem JF, Allerman A, Wendt JR, Sinclair MB, Capolino F, Brener I (2013) Strong coupling in the sub-wavelength limit using metamaterial nanocavities. Nat Commun 4:2882

29. Benz A, Krall M, Schwarz S, Dietze D, Detz H, Andrews AM, Schrenk W, Strasser G, Unterrainer K (2014) Resonant metamaterial detectors based on THz quantum-cascade structures. Sci Rep 4:4269

30. Kalchmair S, Detz H, Cole GD, Andrews AM, Kleng P, Nobile M, Gansch R, Ostermaier C, Schrenk W, Strasser G (2011) Photonic crystal slab quantum well infrared photodetector. Appl Phys Lett 98:011105

31. Wu C, Shvets G (2012) Design of metamaterial surfaces with broadband absorbance. Opt Lett 37:308–310

32. Vora A, Gawami J, Pala N, Kulkarni A, Pearce JM, Guney D (2014) Exchanging ohmic losses in metamaterial absorbers with useful optical absorption for photovoltaics. Sci Rep 4:4901

33. Li Q, Li ZF, Li N, Chen XS, Chen PP, Shen XC, Lu W (2014) High-polarization-discriminating infrared detection using a single quantum well sandwiched in plasmonic micro-cavity. Sci Rep 4:6362

34. Li W, Coppens ZJ, Besteiro LV, Wang WY, Govorov AO, Valentine J (2015) Circularly polarized light detection with hot electrons in chiral plasmonic metamaterials. Nat Commun 6:3879