# 論 文 の 内 容 の 要 旨

論文題目　Wavelength-selective infrared light emission and detection using modified distributed-Bragg-reflector structures

（改良された分布ブラッグ反射器を用いた波長選択赤外線放射・検出の研究）

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Wavelength-selective absorption of light is required for design of many optical devices, including modulator, photodetector, biosensor, emitter, and optical filter. Surface plasmons (SPs) have been utilized in design of wavelength-selective optical structure for their behaviors of both selective absorbing and enhancing electromagnetic waves in subwavelength metallic structures. As a surface wave of metal, SPs lead to absorption of electromagnetic wave, as a result of free electron oscillation in the metallic structures, which is highly relied on the nature Ohmic losses in metals. Therefore, in order to obtain a high quality factor of resonance, low-loss metal such as Ag, Au and Al are commonly used. The limitation of metals to be chosen, constrains the wavelength-selective SP-based devices for many applications, such as for high temperature, for a good adhesion with dielectric, and for special catalyze use. In addition, these reported SP-based devices rely on two-dimensional/three-dimensional patterned nanostructures, and the fabrication of which involves advanced and costly micro/nanofabrication steps. Therefore, to realize narrowband absorption properties for versatile applications without increasing fabrication complexity, an optical resonance mechanism in a simple structure is required.

As a type of surface wave, optical Tamm state (OTS) has been first proposed in

2005, which exist at the interface between two one-dimensional (1D) distributed-Bragg-reflectors (DBRs). Having a zero in-plane wave vector means that OTS can be excited by light propagating in free space without the need for nanostructures to couple light. Instead of nanostructured metal, loss-less dielectric DBRs contribute to electromagnetic wave confinement, which makes the structure possible to store large energy, and thus the OTS structure is promising to have a better optical behavior in terms of *Q*-factor. Usually, the structure consisting of metal and DBR is classified from OTS structure, and is called as "Tamm plasmon structure" or "TP structure", for its strong absorption by metal. This planar multilayer structures based on OTS/TP have attracted great attention due to their potential applications in high-*Q*-factor perfect absorber. With the idea of modifying the DBR stacks, we demonstrate an improved the wavelength-selectivity of these 1D structures, for applications as thermal emitters and photodetectors.

All matter with a temperature greater than absolute zero emits thermal emission. Thermal emission in mid-infrared (mid-IR or MIR) range (wavelength 2.5~25 μm) provides important light sources for bio-sensing and the detection of gases, since organic chemicals tend to have strong and characteristic absorption resonances (i.e., fingerprint) in the mid-IR range. In order to obtain spectrally resolved information, conventional mid-IR spectroscopy devices use broadband light sources with gratings, which hinder their miniaturization. Therefore, there is a strong motivation to design narrowband thermal emitters as light sources to replace the bulky optical system for portable and low-cost molecular spectroscopy devices. According to Kirchhoff's law, the emittance of a planar surface is equal to its absorptance, and thus, to design a narrowband thermal emitter equivalent to design a perfect absorber in mid-IR range. In order to achieve a high *Q*-factor absorption in mid-IR range, we explored different strategies, including increase last DBR layer thickness in a TP structure, inserting an optical cavity in a TP structure between metal and DBR, and modifying a OTS structure by adding a metallic layer.

First, we start from a TP structure consisting of a Ge/$SiO_2$/Ge DBR on top and an Au mirror at bottom. Sustaining a TP mode at the interface between Au and DBR, the structure exhibits a near-unity absorptance peak at a wavelength around 5 μm. For this well-developed TP resonance, adding extra DBR layers could increase it wavelength selectivity at expense of its high absorptance. We find that the increase the thickness of the Ge layer adjacent to Au (i.e., the last DBR layer) can lead to an improvement in *Q*-factor by at least twice, without losing its high absorption. The improvement of the *Q*-factor is attribute to more energy stored within the structure, and the similar peak absorptance value indicates that the same impedance matching condition with the corresponding standard TP structure. In addition, we prove that the means of increase the last DBR thickness is more efficient than increase thickness of other DBR layers. This theory get proved by experiments, by increasing the last Ge layer in layer from 282 nm to 910 nm, the *Q*-factor of emittance peak at 150 C enhances from 22 to 48 with a similar emittance above 0.9.

By inserting an optical cavity with half wavelength optical thickness between DBR and metal, we report a four times enhancement of *Q*-factor compared without much change in absorptance. From the near-field (electric field distribution), the inserted optical cavity sustains a pronounced standing-wave pattern and thus much larger energy can be stored, leading to an enhancement of *Q* value; the similar peak absorptance value indicates that impedance matching condition keeps similar with the structure of the standard TP structure without cavity. The structure is fabricated and achieve a peak emittance as high as 0.9 with a *Q*-factor of 88, giving the highest *Q* value at that time. The proposed method of inserting cavity in standard TP structure provides a means to drastically enhance the *Q*-factor without changing the large absorptance, and thus it has been widely applied in design of many optical devices.

Due to the large absorption losses induced by the metallic films, TP structure has a limited *Q*-factor. Without any metallic film, the OTS structure using two loss-less DBRs to store energy may offer a means to improve the *Q* value of thermal emitters in a 1D configuration. With this idea, we demonstrate 1D structure consisting of a Ge/$SiO_2$ OTS structure and a Pt mirror at bottom and realize narrow-band and wavelength-tunable thermal emission in the mid-infrared range. At the resonance wavelength, light is confined between the two loss-less DBRs of the hybrid metal-OTS structure leading to resonance with a high *Q*-factor (over 1000 is achieved through simulation) and the bottom metallic mirror blocks the light from leaking out thus providing an inelastic loss channel that guarantees a pronounced absorptance peak. As a result, the approach of modifying an OTS structure by adding a metallic layer, leads to a *Q*-factor of 780, giving it the highest *Q*-factor yet reported for a thermal emitter. Moreover, thermo-optic effect of Ge is significantly influence the peak, in the case of this narrow peak. As a result, this sharp emission peak can be actively tune within a range as large as 4.6 times of its bandwidth by controlling the operating temperature. Note that the fingerprints in mid-IR range usually correspond to a resonance with a *Q*-factor less than 200. Thus, the demonstrated thermal emitter is possible for actual use as light sources in portable chemical- and bio-sensing device.

In another part of my research, designing and improving of TP structures for wavelength-selective hot carrier photodetection are demonstrated. In SP and TP structures, accompanied by photons absorbed in metals, hot carriers can be generated. Extracted via internal photoemission, the hot carriers enable below-bandgap photodetection, and high tunability of the working wavelength by manipulating the structured resonance instead of the materials. Relying on this mechanism, many low-cost semiconductors (e.g., Si, ZnO, $TiO_2$) are possible to be utilized beyond the band-to-band limitations and extend even to near-infrared range, which may decrease the cost for a near-infrared photodetector. Indeed, direct illumination on a metal film can excite hot carriers, but with effective light-trapping mechanisms by SP and TP, generation of hot carriers can be improved at resonance wavelength, realizing a much efficient and wavelength-selective photodetection. Hot carrier photodetection relying on SP has been demonstrated since 2010, but all of the above require 2D or 3D nanofabrication processes that are costly, and this hinders their practical use. Therefore, to realize narrowband emission over a large-area without increasing fabrication complexity, a planar multilayer structure based on surface-state resonances offers many advantages over 2D or 3D nanostructures.

We report a hot electron photodetector consisting of a modified Ge/$SiO_2$ DBR structure and an Au/Ti–ZnO–ITO hot electron device on top. ZnO is a well-known semiconductor with a bandgap energy corresponding to a photon in UV range, but utilizing the hot electron internal photoemission from metallic film (Au/Ti) into ZnO, we report a photoresponse even for telecommunication wavelength (around 1550 nm). An anisotropic light absorption in the metallic film (Au/Ti) and the ITO film leading to a predominant hot electron generation primarily in the metal film and transport of these hot electrons from the metallic film to the ITO film. The Au/Ti layers not only act as a hot-electron generator, but also contribute to wavelength dependent photoresponse, for constituting a TP structure with DBR underneath. For an even pronounced wavelength-selective behavior, we modified DBR by increasing the last DBR layer thickness, enabling a wavelength-selective absorptance peak with bandwidth of only 43 nm, which can be monitored by a change of the photoresponse at zero bias. As a result, a wavelength-selective photodetection was demonstrated in the C- and L-band of telecommunication wavelengths (from 1529 to 1607 nm). It is for the first time that a TP-based photodetector is experimentally demonstrated, which reveals the significant of this work.