論 文 の 内 容 の 要 旨

論文題目　Design and Characterization of Plasmonic Nanowire Quantum Dot Lasers
（プラズモニックナノワイヤ量子ドットレーザの設計と評価に関する研究）

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Plasmonics is the study of the coherent oscillation of electrons at the interface between a metal and a dielectric, known as surface plasmons as they resemble the electronic oscillations in a plasma gas. The term "plasmonics" was first coined in Caltech in the early 2000s, for a new device technology that exploits the unique optical properties of nanoscale metallic structures to route and manipulate light at the nanoscale. Surface plasmons are electromagnetic waves and thus travel at the speed of light, but with subwavelength confinement due to exponential decay from the metal-dielectric interface. This property has since been widely employed to miniaturize optical devices to spatial dimensions comparable to that of their electrical device counterparts, which is below the diffraction limit of light and thus cannot be achieved with conventional optics, for the purpose of monolithic, high density integration of electrical and optical components.

The replacement of electrons with photons as information carriers provides many advantages such as higher bandwidths and operation speed, and this is one of the main motivations for optoelectronic integration. A key ingredient for the realization of such hybrid circuitry is the nanolaser: a coherent source of photons at the nanoscale. The past decade has seen huge research efforts in reducing the size of conventional lasers below the diffraction limit. Various approaches using photonic crystals, metallic cavities, and plasmonic structures have been explored. Despite the drawback of higher losses, plasmonic nanolasers, particularly those based on nanowires, has been a popular research topic as they are promising for achieving enhanced light-matter interactions and enhanced spontaneous emission coupling factors. Recent advances in plasmonic nanowire lasers have made significant progress towards the point where practical applications are becoming viable, but there exists several avenues for further improvement. In particular, nanowire plasmonic lasers to date are based on semiconductor materials that emit in the visible range, but emission in the near infrared range of ~800 nm to 1100 nm is desirable for high-speed short reach interconnects. For improved device performance, the use of quantum wells or quantum dots embedded within the nanowires is also desirable due to better carrier confinement. The current plasmonic nanowire design based on the hybrid plasmonic-waveguide mode supported in a dielectric layer between the nanowire and the metal layer exhibits poor mode confinement within the nanowire core region, and coupling to quantum structures in the nanowire is expected to be poor.

In this thesis, the problems raised above are addressed, and original research on the fabrication and optical properties of plasmonic AlGaAs-GaAs core-shell nanowire lasers are presented. The feasibility of achieving sufficient gain for plasmonic lasing with InGaAs quantum dots embedded in GaAs nanowires was demonstrated experimentally.

A brief outline of the thesis is as follows. Chapter 1 is the introduction which provides a context for research on plasmonics, giving a brief history and broad overview of this field with a focus on subdiffraction limit optical devices. In Chapter 2, basic principles on plasmonics and details on computational methods used in this thesis are described. A variety of computational methods, including finite-difference frequency domain, finite-difference time domain and also finite element methods are used to design and characterize the plasmonic nanowire lasers. Properties such as field distribution of the plasmonic modes, mode losses, confinement factor of the plasmonic mode to the nanowire cavity, reflectivity at the nanowire end facets and Purcell factor enhancements that are important for the design and characterization of the plasmonic nanowire laser can be numerically calculated using these methods.

In order to achieve plasmonic lasing with quantum dots as the gain medium, it is desirable to place the nanowires in direct contact with the metal layer for better mode overlap with the quantum dots, but this simultaneously increases the losses of the supported mode significantly. Therefore, it is necessary to suppress the increase in propagation losses due to blemishes in the silver film. Chapter 3 describes the fabrication of a high quality silver film in terms of surface roughness and single crystallinity, which is the basic building block for high performance plasmonic lasers. The characterization of the silver film properties are also performed and detailed in this chapter.

The next goal is to demonstrate plasmonic lasing using bulk GaAs which is expected to have much higher gain as a feasibility check. The fabrication, characterization, and optical properties of such bulk GaAs nanowire plasmonic lasers are described in Chapter 4.

Chapter 5 describes the fabrication and demonstration of the plasmonic nanowire quantum dot laser. Quantum dots are desirable as a gain medium due to their superior carrier confinement and density of states compared to bulk semiconductor materials. However, quantum dot lasers so far are limited to dielectric optical cavities that are diffraction limited. There has yet to be reports on using quantum dots to achieve sub-diffraction limit lasing in plasmonic lasers. The first demonstration of such a laser is reported here. Finally, the conclusion to this thesis is presented in Chapter 6. Implications of the results, as well as future research directions and possible developments will be discussed.

An appendix section on the design of an efficient plasmonic modulator based on graphene as the active material is also included. Modulators are another important component in optical circuitry, and can also be reduced in size by using plasmonics. In this section, modulation performance was studied using finite-difference time domain methods, and a metal-insulator-metal waveguide on top of a graphene layer was proposed as an efficient plasmonic modulator design.