氏　　　　　　名	にしの　ひとし 西野　仁
研究科，専攻の名称	東北大学大学院工学研究科（博士課程）機械機能創成専攻
学 位 論 文 題 目	光量子原子時計のための反射型ガスセル
論 文 審 査 委 員	主査　東北大学教授　小野　崇人 東北大学教授　高　偉　東北大学教授　金森　義明 東北大学准教授　戸田　雅也　主任　原　基揚 （情報通信研究機構）

論文内容要約

Optical quantum atomic clocks for frequency references provide the base for many applications such as digital communication, navigation systems, synchronization of networks, and electric power distribution. As the amount of transferred data increases and data rates become faster, more requirements are placed on the timing systems. At the same time mobile applications require miniature and low power frequency references. Also, micro atomic clock is expected to be a great benefit to various applications such as autonomous vehicle navigation systems in 5G network, and autonomous controlled drones in medical or agriculture field etc. The miniaturization of atomic clocks has been accomplished thanks to three breakthroughs. The first is novel interrogation scheme of atomic resonance, In the micro atomic clocks, the coherent population trapping (CPT) is generally used to observe a microwave transition of alkali atom. In this scheme, alkali atoms are irradiated by the bichromatic lasers and the transmitted light intensity is measured. The CPT phenomena occurs only when the frequency difference of the two lasers equals to the microwave transition. In such a situation, because the atoms do not interact to the lasers, the signal of sharp atomic resonance can be obtained by measuring varies of the transmitted light intensity. This scheme has advantages to reduce the size and power consumption of physics package since the physics package can consist of all optical components unlike the conventional method that uses microwave cavity with large power and occupies a large volume. The second breakthrough is the progress of semiconductor laser. To measure the CPT resonance, it needs to prepare the two lasers. From 2000's, the VCSEL, which satisfy the requirements such as small size, low consumption, high speed modulation and room temperature operation, became able to be manufactured. The third breakthrough is the progress of microfabrication technologies. Although, conventional glass-blown gas cell is not suitable for reducing the size and cost, recently, the mass-producible gas-cell can be made by microfabrication technique. The physics package of micro atomic clocks generally consists of a VCSEL, a quarter wave plate, micro lenses, a vapor cell and a photodiode. These components are stacked to the direction of the wafer thickness and the total thickness becomes the sum of each component. Recently, reflection type vapor cells with reflection mirrors have been developed. The total thickness including the vapor cell and

optical components can be decreased and the wafer level packaging can be done more easily. In this reflection-type vapor cell, a number of alkaline atoms interacting with the laser light can be increased by extending the length of the vapor cell. Thus, because the signal-to-noise ratio could be improved, the short-term frequency stability of atomic clock can be improved.

In chapter 1, background as described above, and the basic theory for the optical quantum atomic clocks is described. The absorption line spectrum for alkali atoms, CPT resonance and the relaxations of alkali atoms in the vapor cell, buffer gases, and frequency stability.

In chapter 2, the basic study for the vapor cells is performed. Normally the way of sealing Rb and buffer gasses is anodic bonding, and Si and Tempax glass are used. It is known that oxygen is generated from the glass surface during anodic bonding, and Tempax glass can react with alkali atom. The emitted gasses could be reacted with Rb, and that cause frequency shift. Then, the gas analysis is performed by fabricating the sample with a cavity, and the tempax glasses with Al_2O_3 coating and without coating are used. Al_2O_3 is for barrier layer preventing from reacting with Alkali vapor. After gas analysis, the transmission-type vapor cell is fabricated and evaluated. In the evaluation, the oscillator is incorporated a thin film bulk acoustic resonator (FBAR) having a resonant frequency of fundamental mode in 3.5 GHz band instead of a crystal resonator. It can deliver the electron transition frequency of rubidium atoms in 3.417 GHz without a complicated frequency multiplication using phase locked loop (PLL). This topology can much reduce the system scale and power consumption. Aiming for downsizing the atomic clock system toward chip-level and mass-production, microfabricated vapor cell containing Rb and N_2 gasses is developed in further. Applying these micro components into the atomic-clock-test-bench, clock operation with short-term frequency stability of 2.1×10^{-11} at 1 s is achieved.

In chapter 3, the design, fabrication and evaluation of a reflection-type optical Rb vapor cell for chip-scale micro atomic clocks. To reduce the physical package height and improve signal-to-noise ratio, the reflection-type vapor cell is developed. The optical components, which are a VCSEL, lens, waveplate, ND filter, and photodiode, can be mounted on one-side of the vapor cell. A (100)-oriented Si wafer with cut off 9.74° toward [011] direction is used to make 45° mirrors by anisotropic wet-etching. 90° mirrors are fabricated by Si deep reactive ion etching and surface planarization by H_2 annealing. For fabricating 90° mirrors, the etching machines, recipes, mask patterns, resists are investigated and optimized with (100)-oriented Si wafer with cut off 9.74° toward [011] direction. Thought the optimization of 90° mirrors, heat-resistant resist is used for avoiding the undesired etching at the etched surface by Si deep RIE. By using the heat-resistant resist the error angle from 90° is achieved under ± 0.1°. The fabricating process of the reflection-type vapor cell is combination of the wet-etching for 45° mirrors, dry-etching process for 90° mirrors, and anodic bonding. After fabricating the vapor cells, the evaluation is performed, the optical absorption line of Rb atoms and CPT resonance peak is measured and compared with the theoretical calculation. Then the reflection-type vapor cells with mirrors deposited gold and with mirrors deposited gold and Al_2O_3. The Al_2O_3 is for protecting a reaction with alkali atoms. After fabricating, it is found that the vapor cells easily can react with the alkali atoms regardless the barrier layer of Al_2O_3. Then it is concluded that reflective films used for a reflecton-type vapor cell should be used to use non-reactive and high reflectance films like dielectric multi-layers. It is concluded in this chapter that the results by using Si mirror indicate that the vapor cell may realize a chip-scale micro atomic clock with a reduced height on the base-plate of the system, and the result by using gold mirror can lead to fabricate the reflection-type vapor cells with higher performance by using the knowledge from the results.

In chapter 4, considering the conclusion from chapter 3, the design, fabrication and evaluation of a reflection type planar optical alkaline atom vapor cell integrating 45° mirrors in the vapor cell for micro atomic clocks. The design of the cell structure is very simple and has an ideal structure with mirrors deposited the dielectric multi-layers, and 45° mirrors, which can be integrated in the vapor cell, are also developed. The 45° mirrors made of glass substrates are fabricated by dicing process and the mirrors are deposited reflection films before dicing the glass substrates. A novel assembling and local anodic bonding method for fabricating the glass 45° mirrors is developed. The vapor cells are designed to be 2, 4, 6, and 8 mm of optical path length, and their absorption are evaluated and compared with calculation. CPT (Coherent Population Trapping) resonance for atomic clock operation is also confirmed and compared with calculation results. Allan deviation is measured, and the result shows the dependency of the optical length in the vapor cell. The clock operation with short-term frequency stability of 5.2×10^{-11} at 1 s is achieved using the fabricated reflection-type vapor cells with glass 45° mirrors. In addition, the improvement of the short-term frequency stability by increasing the optical length in the vapor cell is shown by comparing the 2 mm-long with 6 mm-long vapor cells. Observed Allan deviations are 2.2×10^{-10} and 9.5×10^{-11} with averaging time $\tau = 1$ s for 2 mm-long and 6 mm-long vapor cells, respectively. The result shows that without increasing the size in the thickness direction the short-term frequency stability can be improved. It is concluded in this chapter that the proposed reflection-type planar vapor cell is promising to be applied to chip-scale micro atomic clocks with system-in-package.

In chapter 5, the conclusion is described, and the performance from the reflection-type vapor cell is indicated comparing with other chip-scale atomic clocks.

In summary, this thesis has successfully developed the reflection-type vapor cell for the optical quantum atomic clocks.