Graduate School of Pure and Applied Science

Chalcogenide Plasmonic Devices Employing Photo- and Electrical- Induced Phase Transition

(光および電気誘起相転移を用いたカルコゲナイドプラズモニックデバイス)

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Abstract

Recently, high-speed, ultra-compact and power-efficient optical communication devices are in the spotlight of research, to provide the high-capacity transmission for information and communications. The silicon-based dielectric optical devices are highly attracting attention. In these devices, the waveguide length needs more than 100 μm because the diffraction limit of the light and the weak light-dielectric interaction. [1-3] To solve these problems, surface plasmons polaritons (SPP) have recently attracted attention. SPPs are collective oscillations of free electrons of metal. When SPP waves propagate along a metal-insulator interface, the electromagnetic field is localized at the interface. [4-6] The spatial distribution of electromagnetic fields in the plasmonic waveguide are reduced and the SPP-matter interactions are enhanced because of the strong field confinement effects of SPP. Therefore, the waveguide length can be smaller than the diffraction limit. For this reason, sub-wavelength scale plasmonic opto-electrical devices are researched. [7-10] In the case of “Metal-oxide-Si” plasmonic modulator, the modulation is operated by applying the gate voltage to MOS structure. [11] The “Metal-Insulator-Metal” plasmonic modulator realized the phase modulation using non-linear material. [12] In the case of using phase-change material, optical contrasts are utilized for intensity modulation. [13, 14]

Chalcogenide phase-change materials have the large contrasts of optical and electrical property between the crystalline and the amorphous phase. The $Ge_2Sb_2Te_5$ alloy (GST-alloy), which is typical phase-change material, is widely used for the recording layer of optical discs or non-volatile memories. [15-17] In recent year, the $[(GeTe)_2/(Sb_2Te_3)_1]_n$ superlattice (GST-SL) is developed. [18-20] The phase transition of GST-SL is caused by applying optical or electrical pulses. That phase transition is not

through the liquid phase. Therefore, the GST-SL possesses an advantage over the GST-alloy particularly in the smaller energy consumption and fast transition time.

The interfacial phase-change memory (iPCM), which is typical application of GST-SL, has been reported. The cell size of GST-SL in the iPCM is only 100 nm square. The non-volatile plasmonic devices using GST-SL is expected to achieve the smaller energy consumption and fast switching time. That device needs a large area of the cell size more than a few microns because of SPP-GST-SL interaction. However, the reversible phase transition of GST-SL in that large area has not been reported.

In this thesis, we investigate the electrical-induced reversible phase transition of the GST-SL which is embedded with the plasmonic waveguide. To design the “metal-low refractive index-high refractive index” hybrid plasmonic waveguide (HPW), we simulated the electromagnetic fields using Finite Difference Time Domain (FDTD) method. To fabricate the HPW, we applied photolithography process and focused ion beam etching. In addition, we describe the photo-induced irreversible phase transition and the results of numerical analysis of the propagating mode in the multiple layered “complex-dielectric” medium such as GST-SL.

Design of HPW using the FDTD simulation

In order to apply the electrical pulses to the GST-SL and guide the telecom-wavelength light (λ = 1.55 μm) in the waveguide, the indium tin oxide (ITO) was choose as an electrode and core layer of the waveguide. We considered the multiple layered “Si_3N_4 (clad)/ ITO (core)/ Au” hybrid plasmonic waveguide using FDTD numerical simulation. The Si_3N_4 clad layer was partially replaced to the GST-SL and another ITO layer was placed on the GST-SL. In this FDTD simulation, the optical property of the GST-SL in the high-resistive (RESET) and low-resistive (SET) phase were defined by the Lorentz-Drude dielectric function which was experimentally measured by the spectroscopic ellipsometer. To estimate the RESET-to-SET extinction ratio, we simulated intensity of electric field after the propagation of waveguide. Moreover, we investigated the extinction ratio in accordance with the thickness of ITO core and Si_3N_4 clad layers. Finally, we obtained maximum extinction ratio 14.7 dB when the thickness of ITO and Si_3N_4 layers were equal to 240 nm and 80 nm, respectively.

Electrical-induced reversible phase transition

The device based on the results of FDTD simulation was fabricated. First of all, SiO_2 (80 nm, sacrifice layer), Si_3N_4 (80 nm, clad layer), ITO (240 nm, core layer), Au (80 nm) and Cr (8 nm, adhesion layer) were sputtered on a 20 nm-square Al_2O_3 substrate Then, photoresist was spin coated and exposed with rectangular shapes (5 μm × 5 ~ 30 μm) by using the maskless lithography system.

After that, uncovered parts of the SiO_2 and Si_3N_4 layer were removed by using a reactive ion etching to make the groove for GST-SL. Next, the GST-SL (80 nm) were deposited by RF sputtering. Then, the GST-SL was removed by ion etching beside that in the groove. Finally, another ITO (40 nm) layer was sputtered on the GST-SL.

We applied the sequence of electrical pulses to the fabricated device between upper ITO layer and lower ITO layer to measure the changes of resistance. Each sequence included 50 electrical pulses. The pulse width, the time interval from falling pulse edge to measurement point and the read voltage were equal to 500 ns, 500 ns and 0.5 V, respectively. The minimum and maximum voltages of the applied pulses were equal to 0.5 V and 5.0 V, respectively. In the typical experimental results, the initial resistance was > 1 MΩ which was corresponding to the RESET (high-resistive) phase. The resistance abruptly decreased to ~ 10 kΩ when applied voltage reached to 1.9 V. This behavior is interpreted as the RESET-to-SET (low-resistive) phase transition of the GST-SL. Moreover, the resistance increased over 1 MΩ when applied voltage reached to 3.2 V. It is suggested that the re-RESET phase transition is occurred. This tendency was reproduced by several measurements, so we observed the electrical-induced reversible phase transition of the GST-SL.

Photo-induced phase transition

The modulation of optical transmittance of telecom-wavelength light (λ = 1.55 μm) through the single slit structure on the multiple layered "Au/ Si_3N_4/ GST-SL" film was investigated. To induce the phase transition of GST-SL, we irradiated the second harmonic wave of Q-switched Nd: YAG laser (λ = 532 nm, pulse width = 6 ns, energy density = 98 mJ/cm^2) with only single pulse. The optical intensity decreased when the phase of the GST-SL changed from the RESET to SET. The obtained maximum modulation was equal to -7.2 %. To consider the origin of modulation due to the phase transition of the GST-SL, we performed numerical simulation using the FDTD method. From that result, we attribute the modulation to the reduction of the field confinement in the slit structure with decreasing the extinction coefficient of the GST-SL.

Analysis of electromagnetic modes in multiple layered complex-dielectric waveguide

The complex refractive index for λ = 1.55 μm of the GST-SL in the RESET and SET phase are $n_{\mathrm{RESET}} = 7.69 + 1.80i$ and $n_{\mathrm{SET}} = 4.66 + 0.10i$, respectively. In particular, the RESET phase has large real and imaginary part of refractive index. Therefore, the propagating electromagnetic wave in the RESET phase of GST-SL slightly oscillates and drastically attenuates. Thus, approximating by real number for the wave number in the GST-SL is not appropriate. The wave number must be treated as complex number. For this reason, we analyzed the propagating electromagnetic fields in the GST-SL to expand the propagation constants (β), which is approximated by real number for traditional analysis, to the complex number.

The GST-SL is "complex-dielectric" medium. Therefore, we considered the two-dimensional "complex-dielectric/ dielectric/ complex-dielectric" slab waveguide. The dielectric medium (air), which had width of $2T$, was sandwiched by the complex-dielectric medium (GST-SL) which had semi-infinite thickness. Here, the refractive index of air (n_{air}) was $n_1 = 1$. On the other hand, the refractive index of GST-SL ($n_{\mathrm{GST\text{-}SL}}$) was complex number. To obtain the character of the spatial distribution of electromagnetic fields, we solve the wave equation under the boundary condition. From that result, we found that the transverse magnetic mode did not affect the diffraction limit of light. When the GST-SL was in the RESET phase, the propagating electromagnetic field was strongly confined in the waveguide. Particularly, the spatial distribution of the electric field corresponds to the SPP propagating mode in the metal/ insulator/ metal waveguide. On the other hand, the electric field penetrated into the GST-SL when that was in the SET phase. We characterized the confinement electromagnetic mode in that waveguide for the first time.

Conclusion

We investigated the electrical-induced reversible phase transition of the GST-SL which is embedded with the hybrid plasmonic waveguide. We fabricated the multiple layered "Si_3N_4 (clad)/ ITO (core)/ Au" HPW based on FDTD numerical simulation. The ITO layer behaved as an electrode and core layer of the waveguide. The Si_3N_4 clad layer was partially replaced to the GST-SL and another ITO layer was placed on the GST-SL. To induce the phase transition, we applied the sequence of electrical pulses to the device including the GST-SL. The resistance abruptly decreased when the voltage reached to 1.9 V. This behavior was interpreted as the RESET-to-SET phase transition of the GST-SL. Moreover, the resistance recovered after applying electrical pulses with the voltage exceeded 3.2 V. It is suggested that the SET-to-RESET phase transition is occurred. We achieved the electrical-induced reversible phase transition of the GST-SL in area of the cell size more than a few microns. Our results suggest the availability of the plasmonic modulator using the GST-SL.

References

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