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Collective optical behavior in complementary wire arrays with Au nanoparticles

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Abstract

Collective optical properties emerge from complementary wire arrays, as determined by using the FTIR (Fourier transform infra-red) spectroscopy. Babinet's effect is clearly observed in the complementary patterns of the wire grating. Such patterns demonstrate the transmittance-enhanced behavior because of surface plasmon resonance of gold (Au) nano-particles on the top pattern surface. Unlike in conventional optical element fabrication, advanced integrated circuit (IC) processing technology is adopted to prepare our complementary pattern samples on a silicon (Si) wafer, and nano-gold-particles are used as the wire conductor in those patterns. The positive pattern is a sample patched with periodic Au wires on the Si wafer. The negative pattern is the adopted as the reverse of the positive pattern; the wire part is empty of Au but the surrounding space is filled with Au particles. This work supports the development of multi-functional optical components integrated in nano-scale semiconductor devices.

Keywords: Babinet's effect; Wire grating; Gold nano-particle; Transmittance-enhanced; Optical component; Nano-device

1. Introduction

The nano-era is coming. Fierce competition in the semiconductor industry has led to a reduction in the scale of all technologies. In the IC industry in particular, larger wafers and smaller line width are driving competition and increasing revenues. Thus, multi-functions can be performed in a single unit area as device density increases. However, side-effects become more problematic, negatively affecting IC performance. These effects include parasitic resistance, capacitance and inductance. The next generation involves smaller sizes and a move into the optical era, as communication speed still needs to be improved. In the optical field, integrating various components with various functions in a mono device remains unlikely because the tolerance of the element dimensions required in

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optical device fabrication is narrow. Accordingly, a means of integrating multi-functional optical components into a single device without negative side effects is very important. Optical communication will be main-stream in the nano-era. The simulation technique will become more important in evaluating the performance of the circuit or the system design. Experimental behaviors must be observed and collective properties investigated. Hence, this study elucidates fundamental properties and physical phenomena.

The distinct effects described above will probably emerge simultaneously as devices are shrunk. For instance, the sub-wavelength transmitting behavior [1,2], the double negative value of permeability and permittivity effects [3–5] and Wood's anomaly [6], and even Babinet's effect [7] together demonstrate the specular phenomena. Transmittance is enhanced by the surface plasmon resonance of the metal film on the top of the sub-wavelength grating [8,9]. The degree of enhancement depends on the incident wavelength [10]. Momentum conservation applies between the wave vector of the illuminating light and the reciprocal lattice of the grating array [11]. Thus, the scale of the wire grating is crucial when the wavelength in the application is reduced to the IR regime, or is visible. The grating is likely to act as an optical filter but with enhanced light intensity [12]. Therefore, further scaled-down IC technology is anticipated to meet the requirements of optical application in a single device. Wire gratings exhibit generic patterns and exhibit unique negative electric permittivity (ε) [13]. Many studies also address the combination of with the SRR pattern to exhibit a negative refraction index behavior [3]. The novel property in SRR is with negative permeability (μ) under some corresponding frequencies. They have been established in the microwave region in which both the negativenesses are judged by the resonance (an absorption of incidence energy) [14]. First, FTIR is used to evaluate the negative permittivity. Interestingly, some of the spectrum exhibits Babinet's behavior, as indicated by comparing FTIR responses between the complementary patterns. Babinet's behavior is the most interesting phenomenon, and motivates this study. Simultaneously, Wood's anomaly effect and enhanced transmittance due to surface plasmon resonance are also observed. Additionally, the behavior of Au nanoparticles has recently attracted much attention [15]. It is very useful in various fields, such as bios, optics and nano-electronics, among others. The patterning ability of Au nanoparticles has also been established in our laboratory [16]. This technique is therefore included in this wire array fabrication, with the expectation of finding new phenomena.

A series of meta-material components is fabricated using mature IC technology and nano Au particle handling. Patterns of numerous sizes were prepared to yield the required wavelength. The corresponding wavelengths in the designed samples range from Tera Hz to mid-infrared frequencies. The samples were separated into three groups; one investigated using a Tera Hz laser, the second using FTIR equipment and the third using CO_2 laser. The CO_2 result related to the SRR sample was presented in [17], and the resulting SRR pattern measured by FTIR was also reported in our recent work [18]. This work focuses on a fast evaluation step to elucidate the optical characteristics of a wire array using FTIR equipment. The phenomenon will be described following the experiment. Section 2 presents the experiment and the characteristics of complementary wire array. Section 3 reports the main results and discusses the experimental data. Section 4 draws conclusions.

2. Experiment

The desired patterned samples were fabricated by the standard IC processes. The substrate is a 6″ double-polished n-type silicon wafer. The wafer is cleaned by RCA cleaning. The processes associated with negatively and positively patterned samples are detailed in [18], and schematic depicted in Fig. 1. For the positive sample [17], the conducting parts of the pattern are filled with Au metal. That is, the positive and negative samples show a complementary property at both patterns. Accordingly, in the negative pattern, the space that surrounds the conducting parts is filled with gold particles, so the conducting parts are empty, with-