Abstract

1. Introduction

Plasmonics in the mid-infrared (IR) range has gained increasing attention [1,2], because of potential applications to surface-enhanced spectroscopy [3,4], chemical/bio sensing [5], thermal radiation control [6], optoelectronic circuit [7,8], nonlinear light-matter interactions [9], etc. Surface plasmons (SPs), including surface plasmon polaritons (SPPs) and localized surface plasmons (LSPs), can be excited on noble metals at mid-IR wavelengths as well as at visible wavelengths. The behaviors of metal SPs, however, vary according to operating wavelengths.

At visible wavelengths, SPPs at metal/air interfaces are closely bound to the material surface, exhibiting wavelength shortening and large Ohmic loss. At mid-IR wavelengths, on the other hand, the SPs are weakly bound to the material surface, exhibiting subtle wavelength shortening and small Ohmic loss. Therefore, materials with plasma frequencies at mid-IR wavelengths (e.g., graphene and highly-doped semiconductors [2]) are suited for applications that require subwavelength confinement in the mid-IR, but noble metals are advantageous in applications where any of small loss, long propagation length, and large electric-field enhancement in the mid-IR [2,10].

Propagation length of SPPs is an important physical quantity that characterizes plasmonic materials. First, it sets the upper limit of device size when applied to practical devices like sensors and optoelectronic circuits. Second, it is a direct measure of the Ohmic loss which underlies the degree of electric-field enhancement obtainable upon SP excitation. Here we note that the electric-field enhancement plays a key role in most of the plasmonic applications. In general, damping of SPs is composed of radiative damping and irradiative damping [11]. Radiative damping occurs by coupling with free-propagating light, and its rate strongly depends on size and shape of each metal structure. Irradiative damping, on the other hand, originates from scattering of free electrons by electrons, phonons, defects, impurities, surfaces, boundaries, etc., and is inherent to each material and its morphology. Therefore, the SPP propagation length not only provides the measures of performances in applications, but also helps us understand the physics behind the Ohmic loss.

Among noble metals, gold is an excellent plasmonic material, because of its high metallic conductivity and superior chemical stability [12]. Although there have been a report on the propagation length of mid-IR SPPs at copper/air interface [13], a report on the propagation length of visible SPPs at gold/air interface [14], and studies on IR dielectric function of gold in relation to morphology [15,16], there has been no report, to the best of our knowledge, on the propagation length of mid-IR SPPs at gold/air interface.

In this paper, we report experimental studies on propagation length of SPPs at gold/air interfaces at a mid-IR wavelength of 10.6 m. We showed that the SPPs propagates for a distance about 10 mm, in agreement with the value predicted from the dielectric constant of polycrystalline gold. In addition, we correlated the SPP propagation length with surface morphology, where surface morphology of polycrystalline gold was modified by thermal annealing and characterized by atomic force microscopy (AFM). Then, the SPP propagation length was demonstrated to increase with increased grain size and suppressed surface roughness, both of which were induced by simple thermal annealing treatment.

4. Results

Figure 4 shows AFM topography images of the surface of the waveguide for the sample (a), (b), and (c). The granular pattern typical for polycrystalline gold is clearly observed for the as-grown sample (Fig.4a). In contrast, the granular pattern is not clear and continuous stretch of a grain seems much larger for annealed samples (shown in Figs. 4b,c). Here we estimate average grain size and aspect ratio of each grain by using the watershed algorithm [a reference is required]. Assuming that each grain has spherical shape, grain diameter is estimated to be 70nm, 190nm, and 180nm, for the sample (a), (b), and (c), respectively (how much is the error bar?). Aspect ratio of the grain is estimated to be 1.60.8, 2.42.5, and 2.01.8 for the sample (a), (b), and (c), respectively. Surface roughness is estimated to be 5.7 nm, 2.8 nm, and 2.2 nm (2.1 nm?) for the sample (a), (b), and (c), respectively, by calculating two-dimensional root mean squares of deviations in height data. In this way, the surface morphology changed drastically by the thermal annealing, characterized by decreased surface roughness and increased crystal grain size.

The SPP-light coupling efficiency of each of the input and output couplers is estimated to be 0.18 in our experiments. Although optimum incident angle for the maximum excitation efficiency of SPP shifted by about 0.5o upon annealing, the change in the SPP-light coupling efficiency was not observed. Deformation of the grating structures upon annealing was not observed by the AFM measurements, either.

5. Discussions

Thermal annealing is a convenient method for controlling material morphology of gold [], especially increasing grain size of polycrystalline. It has, however, minor side effect that pinholes may be generated on metal surface. In fact, pinholes with diameters of <1 m appeared with a number density of 0.16 m-2 after the first annealing process, and with a number density of 0.44 m-2 after the second annealing process. Such pinholes are much smaller than the SPP wavelength but may scatter SPPs and reduce the SPP propagation length. Although we are not able to evaluate quantitatively the SPP propagation loss due to scattering at pinholes, it would be safely concluded that the increase of the propagation length due to the morphology change was more than the decrease of the propagation length due to the pinholes.

6. Conclusions

We experimentally measured the propagation length of SPPs along gold/air interface at mid-IR range, for the first time, to the best of our knowledge. We experimentally showed that SPPs at gold/air interface propagate as long as >10mm at a wavelength of 10.6 m. The measured propagation length is in good agreement with the value predicted from the dielectric constant of polycrystalline gold. We also demonstrated that the SPP propagation length increases with the morphology change (increased monocrystalline grain size and suppressed surface roughness) induced by thermal annealing process.

Quantitative evaluation of the SPP propagation length, demonstrated in this paper, is important in designing plasmonic devices and beneficial for deeper understandings of mid-IR plasmonics.

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