Study of radiative losses of terahertz surface plasmons on plane metal-dielectric interfaces

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***Abstract*—Radiative losses of terahertz surface plasmons (SPs) on plane metal-dielectric interfaces have been studied. Experiments performed with "gold - zinc sulfate – air" plane structures at a 130 μm wavelength have shown that a thin-film dielectric coating of the metal of about λ/500 thickness could double the SP propagation length. In addition, an optimal dielectric layer thickness corresponding to the minimum total SPs energy loss has been found. Experiments with two sets of samples of different quality of preparation combined with atomic force microscopy surface characterization demonstrated the influence of surface structure (roughness, grain, layer thickness uniformity) on the propagation length and optimal dielectric layer thickness.**

I. INTRODUCTION

Surface plasmons (SPs) are of great importance for applications in communication systems, optical sensors and material control, the energy losses of SPs playing a crucial role. This phenomenon is well investigated in the visible and near-infrared regions [1], whereas experiments in the terahertz (THz) range have yielded contradicting results: the experimental values of SP propagation lengths on plane metal surfaces were two-three orders less than those predicted by the Drude theory.

There are two obvious assumptions for this phenomenon: (1) the optical properties of the metal surface are considerably different from those of the bulk metal; (2) the surface of the metal contains imperfections (roughness, impurities, etc.) dispersing the SPs and partially transforming them into bulk waves (BWs), that results in SPs additional losses, named "radiative losses" [2]. As improving the quality of evaporated metal films or polished metal surfaces (which able to change the dielectric constant of the surface) is rather expensive and irreproducible, we decided to study THz SPs radiative losses more carefully and to look for a more simple way for decreasing absorption of THz SPs on real plane interfaces.

SPs are inherently nonradiative surface waves. But when the guiding interface has roughness or intrinsic impurities, SPs lose their nonradiative nature and partially convert into BWs, Imperfections add an increment $\Delta k = \Delta k' + i \cdot \Delta k''$ to the wave vector $k_{0SP} = k_{0SP}' + i \cdot k_{0SP}''$ of SPs on a bare metal surface. We assumed that presence of a thin dielectric coating on the guiding surface could increase the SP wave vector to such extent that the most probable value of $\Delta k'$ would be insufficient to fulfill the inequality $k_{SP}' = k_{0SP}' - \Delta k' < k_0$ (here k_0 is the wave vector of BWs in the surrounding medium), necessary for SPs transformation into BWs. Thus radiative losses could be suppressed to some extent, increasing the SPs propagation length.

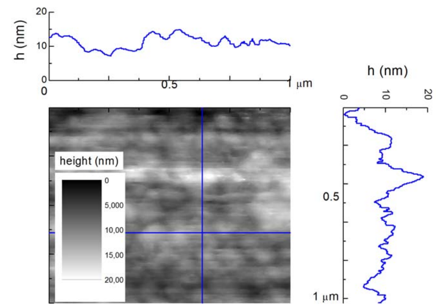

Fig. 1. AFM image of the "imperfect" bare gold surface

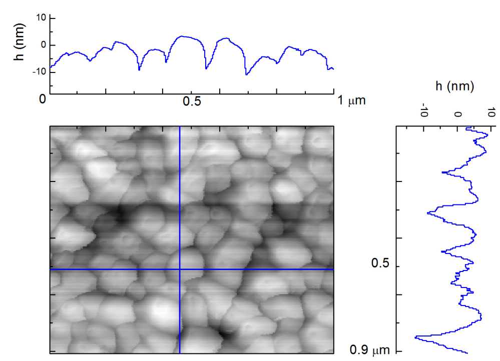

Fig. 2. AFM image of the "perfect" bare gold surface

II. RESULTS AND DISCUSSION

We tested this hypothesis on two groups of samples. The first set of samples consisted of polished glass substrates metalized with a nontransparent gold layer 1 μm thick covered with zinc sulfate (*ZnS*) films using thermal evaporation. The films thickness *d* varied from 0 to 2 μm. The atomic force microscope (AFM) image of a 1×1 μm^2 area of the bare gold surface is shown in Fig. 1.

The surface had a non-regular granular structure with a grain mean diameter of about 90 nm and height of up to 20 nm. These samples were named "imperfect".

The next group of samples, named "perfect", was prepared on high-quality polished glass substrates metalized with a 0.3 μm thick gold layer using magnetron sputtering and covered by 0.07-0.7 μm ZnS layers using e-beam evaporation. In contrast to the previous samples, the bare gold surface had a typical regular granular structure (see Fig. 2), and the thicknesses of the ZnS layers were more uniform along the surface.

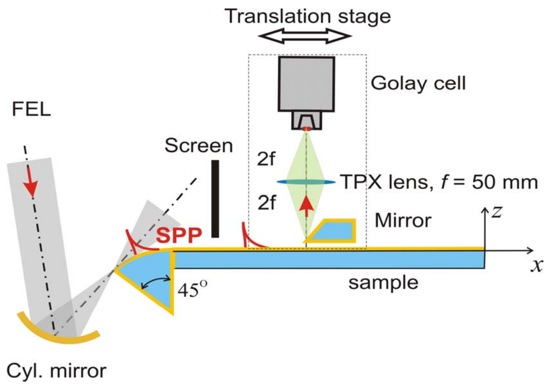

Fig. 3. Experimental setup.

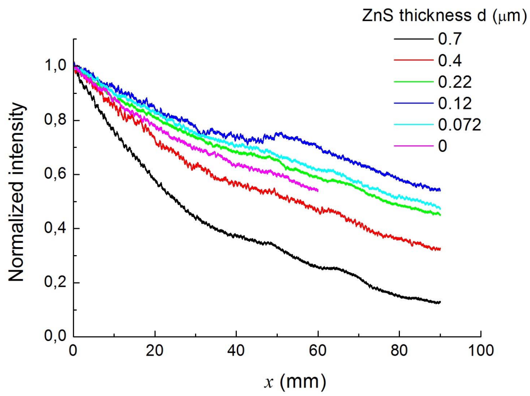

Fig. 4. SP intensity vs. propagation distance *x* for "perfect" samples with ZnS thickness *d*=0-0.7 μm

SPs were excited by free-electron laser radiation with a 130 μm wavelength by the end-fire coupling technique [3] (see Fig. 3) and then detected using an inclined mirror and a Goley cell with TPX lens [4] placed on a translation stage.

Moving the detector along the *x* axis, we measured the SP intensity vs. the propagation distance (Fig. 4) and obtained the SP propagation length *L* from an exponential fitting of the experimental curves. Results for the imperfect samples are shown in Fig. 5. L increased with the *ZnS* thickness *d* growing from zero, reached its maximum at $d_o \approx 0.3$ μm, and then decreased monotonically with further growth of *d*. The increasing *L* for $d = 0$-0.7 μm (two-fold at the maximum) compared with *L* for bare gold ($d = 0$ μm) indicates significant predominance of the SP radiative losses over their Joule losses in gold.

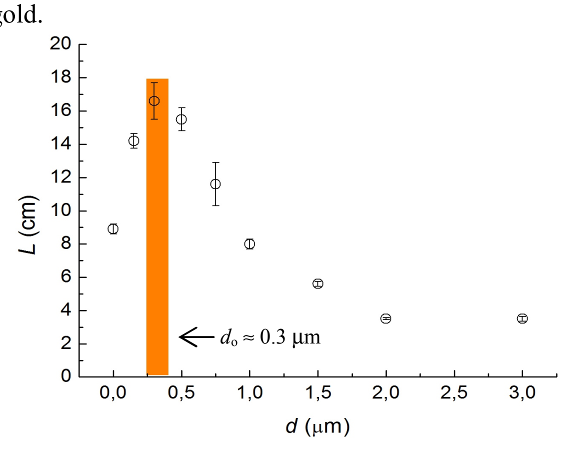

Fig. 5. SP propagation length *L* vs. ZnS thickness *d* for "imperfect" samples

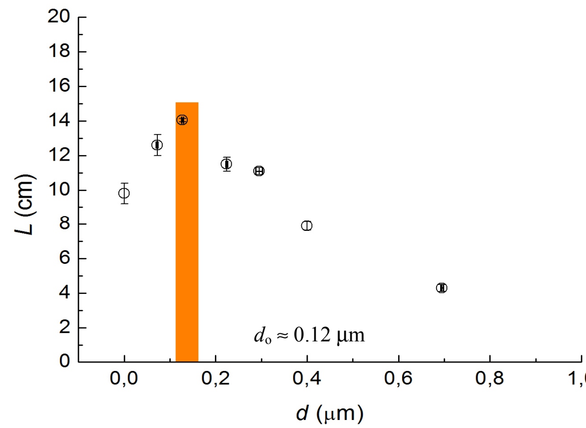

Fig. 6. SP propagation length *L* vs. ZnS thickness *d* for "perfect" samples

The SP propagation length for perfect samples was found (see Fig. 6) to differ not considerably in the absolute value from the imperfect ones and to have a maximum shifted to $d_o \approx 0.12$ μm. Besides, the ratio of the increasing *L* at the maximum to the *L* for bare gold was about 1.4, which is less than for the imperfect samples. These peculiarities indicates that for perfect surfaces (having small roughness and more uniform ZnS layers) the ratio of the radiative losses to the Joule losses in gold is more less than for the imperfect ones.

III. Summary

An experimental analysis of the energy losses of THz SPs confirmed our assumption of significant effect of the radiative mechanism on SP dissipation on surface imperfections. A thin-film dielectric coating of metal increases the surface wave propagation length depending on the surface quality and can be a good protector of SP waveguides used in THz communication transmitting lines.

References

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