Using submicron dielectric coatings to reduce terahertz surface plasmon losses on metals

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Abstract. Terahertz (THz) surface plasmons (SPs) are very promising for developing transmission lines and new photonic devices. Energy losses during propagation of SPs plays important role for these applications. We experimentally studied attenuation of SPs along plane and convex (curvature radius of 60 mm) gold surfaces coated with submicron dielectric (ZnS) layers using monochromatic radiation (λ=130 μm) of the Novosibirsk free-electron laser. The optimal dielectric thicknesses $d^*$, corresponding to the minimum energy losses of SPs, were found. The SP attenuation coefficients $\alpha$ were about 100 times higher for convex surfaces than for plane surfaces, which means intensive radiative losses on the surface bend. A ZnS coating with $d_1^*$=0.025 μm on a plane gold surface reduced $\alpha$ by 20 % as compared with bare gold; coating with $d_2^*$=1 μm on convex surface, three times.

1. Introduction
Currently, studies in the field of terahertz (THz) plasmonics are of great interest because using THz surface plasmons (SPs) is promising for development of transmission lines and new photonic devices [1]. Transmission and processing of information may be several orders faster in THz plasmonic devices as compared with the visible region and can excel the characteristics of existing technologies [2]. Besides, THz SPs propagate on plane metals over tens of centimeters [3], which is much longer than in the visible and near-infrared ranges [4]. Functioning of photonic devices depends much on the SP energy losses because of propagation of SPs along the conducting surface. It is well known that in the THz range the SP attenuation coefficient is about two orders less than the Joule losses calculated by the Drude model of metal conductivity [5-8]. There are two main reasons for this discrepancy. The most probable cause is the difference in the dielectric properties of real metal surface and respective bulk crystal [9]. Another explanation of the great attenuation of THz SPs can be the “radiative” losses of SPs on the roughness and intrinsic inhomogeneity of the surface. The characteristic dimensions of optical surface roughness are usually much less than the THz radiation wavelength. According to the theory [10], it means that the radiative losses (RLs) of SPs are expected to be negligible. However, in recent experiments we found [11] that RLs in the far infrared region could be significant. Also, in the last theoretical paper [12] the analytical...
solution for the propagation of SPs along a 2-D rough metal surface was obtained, from which it follows that there is a roughness-induced energy flux from the surface reradiated into a free space. Estimated calculations showed that a 30 nm roughness can reduce SP propagation length in two times. It can be understood qualitatively if we take into account the small difference between the THz SP wave vector and that of plane waves in the free space, which may lead to intensive SP conversion into bulk waves even on tiny surface imperfections. The role of RLs is even greater on curved surfaces, where it depends on the curvature radius [13]. If a thin dielectric film coats a metal surface, the SP wave vector is increases, leading to the transformation of a surface wave on the imperfections and bends less possible, and as a result decreases the RLs. On the other hand, it is well known that a dielectric coating raises the SP Joule losses due to increase in the field portion of SPs carried inside the metal [14]. These two competitive processes can lead to existence of optimal dielectric thickness, corresponding to minimum total losses of SPs.

In this work, we present experimental results of measuring the energy losses of terahertz SPs propagating along plane and convex metal surfaces coated with submicron dielectric layers. Comparison with theoretical predictions is discussed.

2. Experiments on plane surfaces

As a source of terahertz radiation we used Novosibirsk free electron laser generated monochromatic radiation with the wavelength tuning in the region from 30 to 240 µm [15]. In our experiments we used the wavelength $\lambda = 130$ µm. SPs were launched by end-fire coupling technique [16] on 1/8 part of metalized (Au) glass cylinder (figure 1, (a)) with curvature radius $R = 60$ mm. To obtain maximum coupling efficiency the gold surface was covered with zinc sulphite (ZnS) layer 1 µm thick. The cylinder was used to screen from parasitic bulk waves produced from diffraction on its edge. The generated SPs proceeded from the coupling element to the plane sample adjoining it. Samples were 100x120 mm size glass substrates metalized with a gold layer 0.3 µm thick using magnetron sputtering technique. Optionally the gold surface was coated with 0-1.1 µm thick ZnS films by e-beam evaporation. To change the path $l$ which SPs run on the sample surface we used fixed and movable gold mirrors. SPs were uncoupled on the second cylinder and detected to the edge with the optoacoustic detector (a GC-1D Golay cell with NEP $1.4 \times 10^{-10}$ W/Hz$^{1/2}$). The detector was equipped with metal diaphragm having a 2x10 mm rectangular slit (oriented parallel to the plane of sample surface), cutting off parasitic bulk-waves. The Golay cell was coupled to a lock-in amplifier SR-830 tuned at a 15 Hz chopping frequency.

![Figure 1](image.png)

**Figure 1.** Measuring of SP propagation length on a plane surface: (a) experimental schema; (b) SP propagation length $L$ vs. ZnS layer thickness $d$. In the inset – the comparison with Drude theory.

Using a motorized translation stage attached to the movable mirror, we scanned the SP intensity $I$ vs. the run distance $l$ on samples with different ZnS layer thicknesses $d$. Fitting $I(l)$ with exponential decay functions we obtained SP propagation lengths $L$ (the distance in which the intensity decreases...
by a factor of $e$). The results are shown in figure 1, (b). The propagation length increases with $d$, reaches the maximum at $d^* \approx 0.025 \mu m$, and gradually decreases. The maximum corresponds to minimum energy losses of SPs. The attenuation coefficient of SPs $\alpha = 1/L$ for $d^*$ is about 20 % less than that for a bare gold surface. The existence of optimal dielectric thickness confirms our prediction about the existence of two competitive processes: the dielectric coating reduces the SP radiative losses and increases the Joule losses [11]. Note that the experimental value of the propagation length for bare gold ($L\approx32 cm$) is about 20 times less than the Drude model predicts ($L_{Drude}\approx660 cm$), see the inset in Figure 1b. This discrepancy gradually decreases as the ZnS layer thickness $d$ goes up. One can assume that the main cause of this disagreement is the difference in the dielectric properties of a real metal surface and a respective bulk crystal. Taking for bare metal $L\approx32 cm$ and the decay length of SPs into the air ($\delta\approx1.3 mm$ [7]), one can obtain the dielectric permittivity of gold surface $\varepsilon_{Au} \approx -7987+i*10036$. This value is significantly less than the Drude model predicts for bulk gold ($\varepsilon_{Drude} \approx -101640+i*284090$ at $\lambda = 130 \mu m$).

3. Experiments on convex surfaces

We tested propagation of SPs along a cylindrical surface with a curvature radius $R=60 mm$ (figure 2, (a)). A cylindrical mirror launched the SPs on the edge of the sample. The radiative losses emitted from the SP track were detected with a TPX lens and a Golay cell placed on an optical rail in a 2f-2f arrangement, where $f=100 mm$ is the focal length. The intensity of SP radiative losses $I_{rad}$ is proportional to the intensity of SPs $I_{SP}$ and is expected to decay along the track as $I_{rad} \sim I_{SP} \sim \exp (-\alpha R \theta)$. Basing on this assumption, we recorded $I_{rad}$ vs. deflection angle $\theta$ for different thicknesses $d$ of the ZnS layer and found the propagation lengths $L$ of the SPs (figure 2, (b)). The dependence $L(d)$ has a maximum at $d^* = 1 \mu m$, $L_{max}\approx0.8 cm$, which is about 3 times larger than for a bare gold convex surface. Compared with plane samples, the attenuation coefficients of SPs on convex samples are about 100 times larger due to high radiative losses on the surface band, and minimum energy losses take place at about 40 times higher dielectric thickness $d^*$.

![Figure 2. Measuring of SP radiative losses on a convex surface: (a) experimental schema; (b) $L(d)$.

Summary

We measured propagation lenses $L$ of terahertz SPs along plane and convex ($R=60 mm$) gold surfaces coated with submicron dielectric (ZnS) layers. For both geometries the optimal dielectric thicknesses $d^*$ corresponding maximal $L$ (minimal energy losses) of SPs were observed. For convex surfaces the SP attenuation coefficients $\alpha = 1/L$ were about 100 times higher and $d^*$ was 40 times larger, than for plane surfaces, corresponding to intensive radiative losses on the surface bend. Thus, a thin submicron dielectric coating can significantly reduce energy losses of THz SPs, which is very promising for developing of THz transmission lines and new photonic devices.
References

[1] Atwater H A 2006 The promise of plasmonics Scintific American 296 56–63
[2] MacDonald K F, et al. 2008 Ultrafast active plasmonics Nat. Photonics 3 55–58
[3] Jeon T-I and Grischkowsky D 2006 THz Zenneck surface wave (THz surface plasmon) propagation on a metal sheet Appl. Phys. Lett. 88 061113
[4] Suárez A, Ferrando J, Marques-Hueso A, Diez R, Abargues R, Rodriguez-Cantó P J and Martínez-Pastor J P Nanophotonics 6(5) 1109–1120
[5] Koteles E S and McNeill W H 1981 Far infrared surface plasmon propagation Intern. J. Infrared Millim. Waves 2 361-371
[6] Schlesinger Z, Webb B C and Sievers A J 1981 Attenuation and coupling of far infrared surface plasmons Sol. St. Comm. 39 1035-1039
[7] Gerasimov V V, Knyazev B A, Nikitin A K and Zhizhin G N 2011 A way to determine permittivity of real metal surfaces at terahertz frequencies Appl. Phys. Letters 98 171912
[8] Gerasimov V V, Cherkassky V S, Knyazev B A, Kulipanov G N, Kotelnikov I A, Nikitin A K and Zhizhin G N 2013 Surface plasmon polaritons launched using a terahertz free electron laser: propagating along a gold-ZnS-air interface and decoupling to free waves at the surface tail end Journal of Optical Society of America B 30 2182-2190
[9] Pandey S, Gupta B, Chanana A and Nahata A 2016 Non-Drude like behavior of metals in the terahertz spec tral range Advances in Physics: X 1 176-193
[10] Raether H 1988 Surface plasmons on smooth and rough surfaces and on gratings Springer Tracts in Modern Physics 111 (Springer-Verlag)
[11] Gerasimov V V, Knyazev B A, Lemzyakov A G, Nikitin A K and Zhizhin G N 2016 Growth of terahertz surface plasmon propagation length due to thin-layer dielectric coating Journal of Optical Society of America B 33 (11) 2196-2203
[12] Kotelnikov I and Stupakov G 2016 Dispersion relation of a surface wave at a rough metal-air interface Physical Review A 94 053847
[13] Hasegawa K, Noeckel J U, Deutsch M 2004 Surface plasmon polariton propagation around bends at a metal-dielectric interface Appl. Phys. Lett. 84 1835
[14] Schlesinger Z and Sievers A J 1982 IR surface-plasmon attenuation coefficients for Ge-coated Ag and Au metals Phys. Rev. (B) 26(12) 6444-54
[15] Kulipanov G N, et al. 2015 Novosibirsk free electron laser—facility description and recent experiments IEEE Trans. Terahertz Sci. Technol. 5 798
[16] Stegeman G I, Wallis R F, Maradudin A A 1983 Excitation of surface polaritons by end-fire coupling Optics Letters 8(7) 386-388

Acknowledgments
The experiments were made using the equipment of The Siberian Synchrotron and Terahertz Radiation Center supported by The Ministry of Education and Science of The Russian Federation (project RFMEFI62117X0012) and by the Russian Science Foundation (grant No. 14-50-00080). Authors thank the team of the Novosibirsk free electron laser for assistance in the experiments.