Control of the conducting surface by terahertz surface electromagnetic waves

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Abstract. The paper considers the possibilities of quality control of the conductive surface and detection of objects on it beyond the horizon, as well as microscopy of flat faces of semiconductor products using surface electromagnetic waves (SEWs) of the terahertz (THz) range. The conditions under which such methods of control can be implemented are determined; schemes of devices that implement such measurements are elaborated; estimates of the possibilities of the developed methods for monitoring metal and semiconductor products probed by monochromatic THz radiation in the form of SEWs are given.

One of the main directions of non-destructive testing of a solid surface is its probing by optical radiation. The sensitivity of such sensing increases many times if the incident radiation is converted into surface electromagnetic waves (SEWs) directed by the conductive surface under study. The increase in sensitivity is due to the resonant nature of the interaction of radiation with the plasma of free charge carriers (conduction electrons in a metal or main charge carriers in a semiconductor), resulting in SEWs generation which are a complex of two waves: an evanescent $p$-polarized wave, whose field strength fades exponentially when moving away from the “environment - solid body” interface, and a mechanical wave of the density of free charge carriers in the near-surface layer (whose thickness is approximately equal to the thickness of the skin layer) of the solid. This complex is called surface plasmon-polaritons (SPPs) [1].

Depending on the ratio of the frequency $\omega$ of radiation generating the SPPs and the plasma frequency $\omega_p$ of the solid, the propagation length $L$ (the distance at which the wave intensity decreases by a factor of $e\approx2.718$) of SPPs can either be comparable to the radiation wavelength $\lambda$ at $\omega \leq \omega_p/\sqrt{2}$, or significantly exceed it at $\omega << \omega_p$.

Since the plasma frequencies $\omega_p$ of most noble metals are in the visible range, the calculated values of $L$ at THz frequencies (from 1 to 10 THz) reach meters ($\sim10^4 \cdot \lambda$), which enables to control lengthy surfaces of metal products employing THz SPPs. On the other hand, values of $\omega_p$ for semiconductors and their compounds are related to the THz range [2]. As a result, values of $L$ for THz...
SPPs on semiconductors are comparable with $\lambda$, which makes it possible to probe the surface of a semiconductor item only within the spot illuminated by the incident radiation.

1. Methods and devices for metal surface monitoring using THz SPPs

1.1. Method for quality control of flat faces of metal products flow

The method is based on such features of THz SPPs as their ability to propagate over macroscopic distances, to scatter (as a result of diffraction) on inhomogeneities of the surface, and to cross air gaps between the flat substrates that guide them [3]. It should be noted that in addition to thermal (Joule) losses, SPPs also have radiation losses due to their scattering on inhomogeneities. The radiation losses are proportional to $\omega^2$ and lead to partial transformation of the SPPs into bulk radiation emitted from their track into the surrounding medium [4]. Consequently, the propagation lengths $L$ of THz SPPs along real metal surfaces are an order of magnitude smaller than those calculated for the perfectly uniform metal-vacuum interfaces; nevertheless, these $L$ are quite sufficient to measure the intensity of SPPs after they run distances comparable to the decimetre dimensions of most metal products.

![Figure 1. Schematic of a device for quality control of flat faces of metal products flow employing terahertz surface plasmon-polaritons (SPPs).](image)

Figure 1 shows a scheme of the device that implements the method. The radiation of source 1, diffracting on the edge of metalized cylindrical segment 2, is converted into SPPs. After reaching the second edge of the convex surface, the SPPs are transformed into a bulk wave (BW) with a narrow radiation pattern [5], which captures the edge of the controlled face of product 3, carried by the conveyor belt 4 in the direction perpendicular to the SPP track. After crossing the air gap that separates element 2 from product 3, the radiation diffracts on its edge and generates new SPPs on the controlled face (when the gap is up to $10\lambda$, the efficiency of the SPPs passing through it is at least 90% [3]). Attenuating exponentially, these SPPs reach the opposite edge of the face, diffract on it, and generate radiation that crosses the air gap separating product 3 from element 5 (identical to element 2) that converts the BW to the SPPs detected by receiver 6. An electrical signal proportional to the radiation intensity at the input of receiver 6 is registered by measuring device 7. If inhomogeneity (roughness, embedding) occurs on the path of SPPs propagating along the product facet, this leads to a decrease in the signal. Thus, a sign of the presence of inhomogeneity on product 3, and, consequently, the criterion for its rejection, is that the signal reaches the minimum threshold value set by the operator after calibration according to the reference sample. The method is integral (i.e., it sums up the effect of inhomogeneities on the intensity of SPPs along their entire track) and therefore localizes the discrepancy of the surface quality to the standard only for one coordinate.

1.2. Method for monitoring the metal surface beyond its horizon line

The method is based not only on the fact of the macroscopic propagation length of THz SPPs, but also on their ability to follow the topography (in the plane of incidence of probing radiation) of the surface [6]. Moreover, the radiation losses of SPPs on a convex surface increase (in inverse proportion to the
radius $R$ of its curvature) since in this case the wave vector of SPPs $\vec{k}_{SPP}$ receives (from the surface) a negative additive $\Delta \vec{k}$, as a result of which its difference from the wave vector $\vec{k}_o$ of the plane wave in the environment (vacuum, air) decreases, and the radiation losses of SPPs on the real convex surface (containing inhomogeneities) increase [7]. It is noteworthy that on a perfectly homogeneous convex surface the effect of the transformation of the SPP into a bulk wave would occur at a certain value $R$ corresponding to equality $|\vec{k}_{SPP}| = |\vec{k}_o|$. The radiation losses of SPPs on real surfaces (both flat and convex) can be largely levelled by applying a dielectric coating of a certain subwavelength thickness to it, which leads to an increase in the modulus of $\vec{k}_{SPP}$ and to a decrease in the probability of achieving equality $|\vec{k}_{SPP}| = |\vec{k}_o|$ [8]. Thus, even on the convex surface, the propagation length of THz SPPs remains acceptably large for controlling sufficiently extended faces of metal products.

The features of THz SPPs enabled us to implement over-the-horizon location not in the radio, but in the terahertz range. When developing the method, it was considered that THz SPPs can be reflected from a flat mirror and from an impedance step, which, from an analytical point of view, is a beam-splitting plate. Figures 2 (a, b) present two possible schemes for locating an object disposed onto a conductive surface beyond its horizon line with the help of THz SPPs: scheme (a) enables detecting an object and determining the orientation of its reflecting face relative to the plane of incidence by the $x$-coordinate of photodetector 7. Scheme (b), in addition to the capabilities of scheme (a), enables one to determine the coordinates of the probed point of the object. Figure 2 (c) shows a side view of a conductive sample surface consisting of two faces joined by a rounded edge (the horizon line 5) and one of which contains object 6. Scheme (a) involves splitting of the SPP beam with a beam splitter 4, and scheme (b) – interaction of the reflected SPP beam with a flat mirror 4. A coupling element of the diffraction type, for example, a planar diffraction grating (eschelette), can be used for converting the source radiation into the SPPs. Note that the scheme (b) is preferable not only because of the greater information capabilities, but also because of the higher signal-to-noise ratio, since it does not assume unwanted losses (up to 80%) of the energy of the SPP beam when it interacts with the beam splitter, while the reflection coefficient of SPPs from a mirror is close to one.

![Figure 2](image.jpg)

**Figure 2.** Schemes (top view) for detecting an object 6 onto a conductive surface 3 beyond the horizon line 5 by means of the THz SPP-location method: (a) using a beam splitter; (b) using a flat mirror; (c) side view for the both schemes. Here: 1 – a collimated beam of THz radiation; 2 – a removable element for converting the radiation into SPPs; 3 – a conducting sample with flat faces conjugated by a rounded edge 5 (horizon line); 4 – a beam-splitting plate on the scheme (a) or a flat mirror on the scheme (b); 6 – an object; 7 – a photodetector.
We will briefly describe the method for determining the distance $l$ that separates object 6 from the horizon line 5 and the angle $\alpha$ that characterizes orientation of the reflecting face of the object, when measuring according to the scheme (b). Let us know the shortest distances $s$ and $h$ from the point of incidence of the SPP beam on mirror 4 to the horizon line 5 and to the track of the SPP beam falling on object 6, respectively, as well as the angle of incidence $\beta$ of the SPP beam on mirror 4. From the geometry of the scheme (b) it follows that:

$$\alpha = \beta - 45^o,$$  \hspace{1cm} (1)

$$h/(s + l) = \tan(2\alpha).$$  \hspace{1cm} (2)

Solving the system of equations (1) and (2) with respect to $l$, we get:

$$l = -h \cdot \tan(2\beta) - s.$$  \hspace{1cm} (3)

It should be noted that the results of scanning the SPP beam along the $y$-axis (accompanied by the corresponding shift of the receiver 7) can be used to conclude not only about the homogeneity of the reflective face of object 6 (in the case of its homogeneity the intensity of detected signal remains constant), but also to find out whether this face is flat or curved (in the latter case, the offset of the receiver 7 to the point $x$ corresponding to the maximum signal will be a disproportionate to the shift of the SPP beam along the $y$-axis).

Over-the-horizon THz SPP locators can find applications in the optical and mechanical industry for locating objects on a convex metal surface with limited access to it, in aviation for detecting icing of conductive surfaces of aircrafts and eliminating it, in railway transport for early detection of rails defects and foreign objects on them, in engineering and scientific research for probing objects that are exposed to an aggressive gas environment or ionizing radiation.

2. Method for microscopy of flat faces of semiconductor products using THz SPPs

A method is known for optical microscopy of a conducting surface under the conditions of surface plasmon-polaritons (SPPs) generation by the probing radiation of the visible range employing the method of attenuated total internal reflection (ATR) [9]. A necessary condition for implementing the method is the proximity of the radiation frequency $\omega$ to the plasma frequency $\omega_p$ of the sample material, when, as noted in the Introduction, the SPP propagation length $L$ is comparable to the wavelength $\lambda$ of the radiation. As a consequence, the intensity $I$ and phase $\phi$ of the radiation reflected from the base of the ATR-prism (see figure 3) are determined by the local properties of the reflecting structure. Therefore, presence of inhomogeneities on the surface leads to difference in the efficiency of generation of SPPs in this region of the sample from its values at other points of the structure illuminated.

Figure 3. An illustration of the principle of amplitude SPP-microscopy method; here $R_p$ is the power reflection coefficient of the $p$-component of monochromatic radiation.
by the probing beam of collimated monochromatic radiation. Variations in the intensity $\Delta I$ and phase $\Delta \phi$ of the reflected radiation provide information about the distribution of inhomogeneities over the sample surface. The main advantages of SPP-microscopy are high vertical resolution (up to $10^{-4}\lambda$) and the ability to study low-contrast thin-layer objects (in particular, biological ones) [10].

We will demonstrate the possibility of implementing the SPP-microscopy method in the THz range using the example of indium antimonide ($\text{InSb}$) with intrinsic conductivity. For numerical simulations we use the Drude-Lorentz model to describe the dispersion of the complex dielectric constant of a semiconductor [11]:

\begin{equation}
\varepsilon(\omega) = \varepsilon' + i \varepsilon'' = \varepsilon_{\infty} \left[ 1 + \frac{\omega_L^2 - \omega_T^2}{\omega_L^2 - \omega^2 + i \gamma} \right] - \frac{\omega_p^2}{\omega^2 - (\omega + i \gamma)},
\end{equation}

here $\varepsilon_{\infty}$ is the high-frequency lattice background dielectric constant; $\omega_L$ and $\omega_T$ are the LO and TO frequencies of the lattice oscillations; $\gamma$ is the vibration damping constant of the lattice; $\gamma$ is the damping constant characterizing the free carriers. $\text{InSb}$ with intrinsic conductivity is characterized by the following values of the above mentioned parameters: $\omega_p = 81.0 \text{ cm}^{-1}$; $\omega_L = 190.4 \text{ cm}^{-1}$; $\omega_T = 179.1 \text{ cm}^{-1}$; $\Gamma = 2.86 \text{ cm}^{-1}$; $\gamma = 10.7 \text{ cm}^{-1}$; $\varepsilon_{\infty} = 15.68$ [11].

Calculations by formula (4) have shown that the real part of the dielectric permittivity of indium antimonide becomes negative (a necessary condition for the existence of SPPs) at $\lambda \geq 134 \mu\text{m}$ ($\nu \leq 74.5 \text{ cm}^{-1}$). Let the probing radiation wavelength be $\lambda = 140 \mu\text{m}$, which refers to one of “the transparency windows of the atmosphere” for THz radiation. At this wavelength $\varepsilon_{\text{InSb}} = -1.614 + i \cdot 2.936$ and the SPP propagation length $L \approx 143 \mu\text{m}$, i.e. $L \approx \lambda$. Let the material of the ATR-prism be a weakly dispersing TPX (polymethylpentene) polymer with the refractive index $n = 1.46$; the critical angle $\phi_{cr}$ at the “TPX – Air” interface for the radiation is equal to $43^\circ14'$.

**Figure 4.** Calculated dependences of the reflection coefficient $R_p$ on the angle of incidence $\phi$ of $p$-polarized radiation ($\lambda = 140 \mu\text{m}$) on the "TPX prism - Air gap $h$ – InSb sample" structure: curve 1 – $h = 10 \mu\text{m}$; 2 – $h = 20 \mu\text{m}$; 3 – $h = 30 \mu\text{m}$; 4 – $h = 40 \mu\text{m}$; 5 – $h = 50 \mu\text{m}$. 

First, we calculate the dependence of the power reflection coefficient $R_p$ for the $p$-component of such radiation from the structure “TPX – Air gap of $h$ – InSb” (the Otto scheme for performing SPP-microscopy) in order to determine the optimal (for the generation of SPPs) air gap between the TPX prism and the InSb sample. The results of calculations are shown in figure 4. It can be seen that the minimum value of $R_p$ (equal to 0.04) corresponding to the most effective conversion of the probing radiation into the SPPs (curve 2) is achieved at $h \approx 20 \, \mu m$ and the angle of incidence $\varphi^* \approx 52^\circ45'$.

![Figure 5. Calculated dependences of the reflection coefficient $R_p$ on the angle $\varphi$ of incidence of $p$-polarized radiation ($\lambda = 140 \, \mu m$) on the “TPX prism – Air gap $h = 20 \, \mu m$ – ZnS layer of thickness $d$ – InSb sample” structure: curve 1 – $d = 0$; 2 – $d = 0.5 \, \mu m$; 3 – $d = 1.0 \, \mu m$; 4 – $d = 1.5 \, \mu m$; 5 – $d = 2.0 \, \mu m$.](image)

Now we model the change in curve 2 (figure 4) when applying a non-absorbing layer of zinc sulphide (ZnS) of thickness $d$ and with the refractive index of 2.95 to the surface of the InSb-sample. The simulation results are shown in Figure 5. As one can see, when the angle $\varphi$ of radiation incidence on the TPX-prism base is equal to $\varphi^* \approx 52^\circ45'$ the intensity of reflected radiation changes by about 3.5 times (i.e. by 350%) when a 1 $\mu$m thick ZnS layer is applied to the sample surface ($R_p$ changes from 0.04 at $d=0$ to 0.13 at $d=1.0 \, \mu m$). Since modern meters enable reliable recording of changes in the radiation intensity with an accuracy of up to a fraction of a percent [12], we can say that even in the THz range, the SPP-microscopy method can achieve a vertical resolution of at least 1 nm.

3. Conclusion
It is shown that even in the THz range, precise control of both conducting and semiconducting surfaces is possible if the probing radiation is transformed into surface electromagnetic waves (SEWs), or more exactly, into surface plasmon-polaritons (SPPs). Thus, if the frequency $\omega$ of the probing radiation is comparable to the plasma frequency $\omega_p$ of the material (in the THz range, this condition
is satisfied for semiconductors), the local control of the surface is possible (since the SPPs propagation length $L$ is comparable to the wavelength $\lambda$); if $\omega << \omega_p$ (in this case $L >> \lambda$) then the integral control of the surface using THz SPPs is possible (which is true for metals in the infrared and THz ranges). In both cases, the vertical resolution reaches thousandths of the radiation wavelength. In addition, over-the-horizon location of objects on a metal surface is also possible due to the ability of THz SPPs to propagate over macroscopic (decimetres) distances, to follow the surface relief, and to be reflected from objects (including the surface inhomogeneities) disposed onto the surface.

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