Fast point-size photodetector for submillimeter laser radiation

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Optically pumped submillimeter pulsed gas lasers have recently been adopted widely.[1] One problem which arises in the development and applications of these lasers is determining the structure of the laser beam, whose dimensions are typically on the order of a few millimeters. It is accordingly necessary to develop fast, small-aperture photodetectors, both matrix photodetectors and single ones, for submillimeter radiation. Fast photodetectors which operate on the basis of intraband photoconductivity,[2] the photon drag of electrons,[3,4] or the pyroelectric effect are difficult to use to study the spatial distribution of the intensity of pulsed radiation in narrow laser beams because these detectors have a sensitive area of large diameter (several millimeters or more).

In this letter we describe a fast point-size photodetector for submillimeter laser radiation, whose operation is based on a different physical phenomenon: the change that occurs in the resistance of a metal—semiconductor tunnel junction with a Schottky barrier when radiation is reflected by the plasma of free carriers in the semiconductor.[5-7] The change is due to a deformation of the self-consistent Schottky barrier by the ponderomotive forces which arise from the transfer of momentum from the radiation to the plasma of free carriers during the reflection of the light. As a result the tunneling transmission of the barrier and the conductivity of the tunnel junction increase. Physical limitations are imposed on the response time by the rate of redistribution of nonequilibrium charge among the electrons. These limitations are characterized by the value of RC, where R is the resistance and C the capacitance of the junction. A response time on the order of 10^{-9}-10^{-11} s can be achieved for n-GaAs/Au junctions with reasonable values of the junction area and of the dopant concentration. The area of the junction can be quite small, since advanced technological procedures can easily provide junctions with diameters down to a few microns. The junction fabrication technology is also capable of fabricating matrices that are composed of these elements and have the required size.

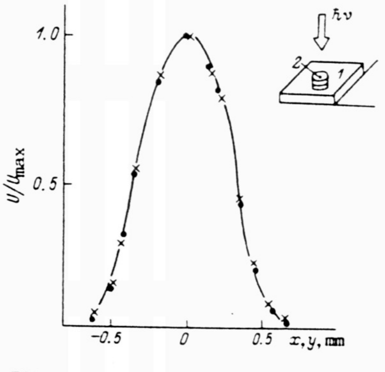

FIG. 1. Coordinate dependence of the photoresponse of the junction. ×) X dependence; ●) Y dependence. The inset shows a detector element. 1) GaAs; 2) gold electrode.

The short response time and small dimensions of the detector element make it suitable for detecting submillimeter laser radiation with a high temporal and spatial resolution. Our purpose in the present study was to analyze the possibilities of using n-GaAs/Au junctions as photodetectors for submillimeter radiation.

The photosensitive element which we studied consisted of an n-GaAs/Au tunnel junction fabricated by depositing the metal on the clean surface of the semiconductor. The impurity concentration in the semiconductor was $(2\text{-}7)\cdot 10^{18}$ cm^{-3}. Figure 1 shows a detector element, fabricated on a wafer of n-GaAs with a thickness of 0.5-1 mm; on one side of the wafer is an ohmic electrode, and on the other is a semitransparent ($d < 200$ Å) gold electrode 1 or 0.25 mm in diameter, which forms the sensitive area of the detector. The transparency of the gold electrode was checked by photothermal spectroscopy. The operation of a tunneling mechanism for the conductivity was monitored by use of the tunneling spectra at liquid-helium temperatures.[8]

We used this photosensitive element to fabricate a photodetector consisting of a tunnel junction in a circuit for measuring the photoconductivity, with a differential amplifier with a bandwidth of 50 MHz, and a gain on the order of 100. The time resolution of the photodetector was ~5 ns, determined by the bandwidth of the amplifier. Measurements at wavelengths λ of 90 and 385 μm revealed that there was no significant change in the sensitivity of the photodetector for the detection of radiation with $\lambda > \lambda_p > 20$ μm. The sensitivity of the photodetector was 0.1 V/kW at a bias voltage ~ 0.5 V and a load resistance of 50 Ω.

A study of the behavior of the signal as a function of the light intensity I over the range from 10 kW/cm² to $2\cdot 10^3$ kW/cm² revealed a weak nonlinearity of the photoresponse, on the order of $I^{3/2}$.

A single tunnel junction 1 mm in diameter was used in this photodetector. To study the coordinate sensitivity of the detector, we scanned the radiation (focused into a spot with a diameter on the order of 0.7 mm) over the area of the gold electrode. The results are shown in Fig. 1; the response decays rapidly as the illuminated region passes out of the area of the metal electrode. These measurements were too crude to allow an evaluation of the maximum attainable spatial resolution as the detector was scanned over the cross section of the laser beam. However, even the results which have been obtained are of interest from the practical standpoint. It would be possible to fabricate detectors with a metal electrode of much smaller diameter (down to 1 μm) and to fabricate matrices of such detectors on a common substrate.

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Resonant frequency doubling of a surface wave in semiconductor–metal waveguide structure

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Layered semiconductor structures are of interest in connection with practical applications in microelectronics. In these structures it is necessary to deal with wave perturbations of fairly large amplitude for which nonlinear effects can no longer be ignored. The linear theory of bounded layered semiconductor structures has been worked out quite comprehensively.[1,2] In the present paper we examine the nonlinear generation of the second harmonic of a surface wave which exists at the interface between a metal and an n-type semiconductor and which propagates along the external magnetic field (the Faraday geometry). If $\omega^2 \ll \omega_e^2$ where ω is the working frequency and ω_e the electron cyclotron frequency, the dependence of the frequency on the wave numbers of these waves is a linear function. Consequently, under the condition $4\omega^2 \ll \omega_e^2$ both the first and second harmonics are natural waves of the structure, for which the space–time synchronization relations $\omega + \omega = 2\omega$ and $k_3(2\omega) = 2k_3(\omega)$ hold,[2] and in a nonlinear medium, there is efficient pumping of energy from the first harmonic to the second and back.

Let us assume that an n-type semiconductor fills the half-space $x > 0$ and that it is bordered at the $x = 0$ plane by an ideally conducting metal surface. A static external magnetic field $\vec{H}_0$ is directed along the z axis. The wave perturbations under consideration propagate along the z axis. We assume that the semiconductor plasma is weakly collisional ($\nu \ll \omega$, where ν is the electron collision rate) and dense ($\Omega_e^2 \omega_e^{-2} \gg \varepsilon_0$, where Ω_e is the electron plasma frequency, and ε_0 is the dielectric constant of the lattice). Under the condition $9\omega^2 \cdot \omega_e^{-2} \lesssim 1$, the third and higher harmonics of the surface wave are not natural perturbations of the structure, so we will ignore them. It can be shown that all of the conditions stated above hold for wide ranges of the parameter values of semiconductors and of the magnetic field. For example, our analysis is valid in samples of n-PbTe ($n_0 \simeq 8 \cdot 10^{17}\,\mathrm{cm}^{-3}$, $m_{\mathrm{eff}} \simeq 10^{-29}$ g, $\nu \simeq 5 \cdot 10^{10}\,\mathrm{s}^{-1}$, $\varepsilon_0 \simeq 400$) for $H_0 = 0.75$-6.7 kOe and n-GaAs ($n_0 \simeq 5 \cdot 10^{17}\,\mathrm{cm}^{-3}$, $m_{\mathrm{eff}} \simeq 6 \cdot 10^{-29}$ g, $\nu \simeq 10^{11}\,\mathrm{s}^{-1}$, $\varepsilon_0 \approx 13$) for $H_0 = 5.5$-10 kOe. The dispersion properties and the topography of the field of these surface waves were studied in the approximation linear in the amplitude of the wave field in Refs. 3 and 4.

The system of equations for A_1 and A_2, the complex amplitudes of the first and second harmonics respectively can be written as follows for the case in which the first harmonic is initially the pump wave:

$$\left(\frac{\partial}{\partial t} + V_g \frac{\partial}{\partial z}\right) A_1 = i\beta_1 A_1^* A_2 + i\beta_2 |A_1|^2 A_1,$$

$$\left(\frac{\partial}{\partial t} + V_g \frac{\partial}{\partial z}\right) A_2 = i\beta_3 A_1^2, \tag{1}$$

where

$$V_g = c\omega_e(\sqrt{2}\,\Omega_e)^{-1}, \quad \beta_1 = \sqrt{2}\,e\Omega_e(10 m_{\mathrm{eff}} c\omega)^{-1},$$

$$\beta_2 = \frac{e^2 \Omega_e^2}{4 m_{\mathrm{eff}}^2 c^2 \omega\omega_e \nu}\left(\frac{33}{80} - 13\frac{\omega}{\omega_e}\right), \quad \beta_3 = \frac{e}{\sqrt{2}\, m_{\mathrm{eff}} c}\,\frac{\Omega_e}{\omega_e},$$

e, m_{eff}, and ν are the charge, effective mass, and collision rate of the electrons, c is the velocity of light in vacuum, V_g is the group velocity of the surface wave, $\beta_{1,3}$ are the coupling coefficients of the first and second harmonics, and β_2 is the self-effect coefficient of the first harmonic. Estimates show that the component of β_2 stemming from the process $0 + \omega = \omega$ is larger by a factor of $\omega\nu^{-1}$ ($\nu \ll \omega$) than that from the process $2\omega - \omega = \omega$. In the second-approximation calculation of the steady-state current (zero pressure) we assumed $\nu \gg k_3 V_{Te}$, where V_{Te} is the electron thermal velocity, so the limit $\nu \to 0$ is not valid.

In the coordinate system moving with the wave ($z' = z - V_g t$, $t = t'$) we set $A_{1,2} = |A_{1,2}| \exp(i\theta_{1,2})$, and using the renormalization $\beta_j \to \beta_i \omega^{-1}$, ($j = 1$-$3$), and transforming to the dimensionless variables $\tau = \omega t'$, $\alpha_1 = |A_1|\sqrt{\beta_1\beta_3}$, $\alpha_2 = |A_2|\beta_1$, $\theta = \theta_2 - 2\theta_1$,

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