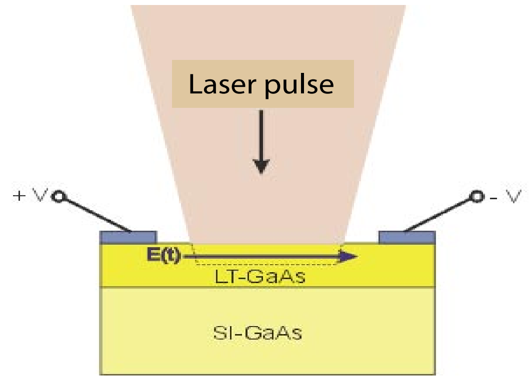
PCA

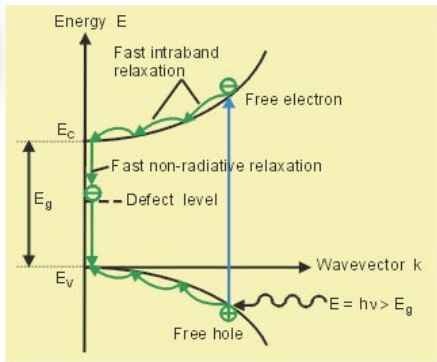
Photoconductive Antenna for THz Applications

A photoconductive antenna (PCA) for terahertz (THz) waves consists of a highly resistive direct semiconductor thin film with two electric contact pads. The film is made in most cases using a III-V compound semiconductor like GaAs. It is epitaxially grown on a semi-insulating GaAs substrate (SI-GaAs), which is also a highly resistive material. The important difference between the SI-GaAs substrate and the film is the relaxation time for excited carriers. In a SI-substrate the carrier lifetime is about 500 ps, but in the film shorter than1 ps.



A short laser puls with puls width < 1 ps is focused between the electric contacts of the PCA. The photons of the laser pulse have a photon energy E = hv ~~n~~ larger than the energy gap Eg and are absorbed in the film. Each absorbed photon creates a free electron in the conduction band and a hole in the valence band of the film and makes them for a short time electrical conducting until the carriers are recombined.

The PCA can be used as THz transmitter as well as THz receiver



- In case of a transmitter a voltage V is connected on the electrical contacts and the excited carriers are accelerated by the electric field during the optical pulse, which results in a short broadband electromagnetic pulse with a time-dependent electrical field E(t) and frequencies in the THz region.

- In case of a receiver a current amplifier is connected on the electrical contacts. During the optical pulse the excited carriers are accelerated by the electric field component of the incident terahertz pulse with the time-dependent electrical field E(t). This leads to a measurable current signal in the outer circuit.

To get the needed short carrier lifetime, the film must include crystal defects. These defects can be created by ion implantation after the film growth or alternatively by a low temperature growth. Low temperature grown GaAs (LT-GaAs) between 200 and 400 °C contains excess arsenic clusters. These clusters create defect levels within the band gap Eg and lead to a fast non-radiative recombination of the electron-hole pairs within a time interval < 1 ps.

PCA applications

As mentioned above, a PCA can be used as a THz emitter or detector in pulse laser gated broadband THz measurement systems for time-domain spectroscopy. Because THz waves penetrate dielectric materials like paper or plastic, are reflected by materials with free electrons like metals and are absorbed by molecules with certain vibration levels within the terahertz band, they have a lot of applications in the fields of time-domain spectroscopy and imaging:

- security checks
- medical imaging
- process control

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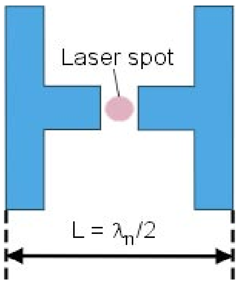
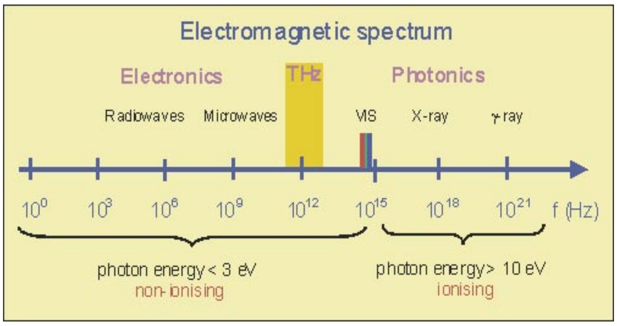
Frequency and wavelength

The photoconductive antenna can be considered as a dipole of the length L, which is in resonance with the electromagnetic wavelength In inside the semiconductor.



The resonance condition is L = m·λn/2 with m = 1, 2, 3,..- integer. The wavelength In in the material with the refractive index n is given by λn = λ/n. Using the wave relation c = λ·f and m = 1, the resonance frequency of the antenna f is given by f = 2·c·n/L with c = 3·10⁸ m/s - speed of light in the vacuum n - refractive index of the semiconductor antenna material L - length of the antenna.



The refractive index n of GaAs at terahertz frequencies is n = 3.4. With this value the first resonant frequency and wavelength of the antenna with the length L can be calculated as follows:

f (THz)	λ (μm)	L (μm)
0.3	1000	147
0.5	600	88
1.0	300	44
1.5	200	29.4
3.0	100	14.7

Security checks:

- Screening passengers for explosives and weapons
- luggage screening
- mail drug screening
- mine detection
- locating water marks in currency
- reading text in envelopes or beneath paint.

Medical imaging

for brest and skin cancer detection and for teeth testing in dentistry. Terahertz waves offers medical benefits:

- Terahertz radiation is nonionizing. That means, it is safe.
- It can penetrate epithelial tissues.
- Laterally image resolution of 250 μm is possible.
- 3-D imaging using amplitude and phase information is possible.

Process control for:

- polymeric compounding
- examining circuit interconnects in packaged ICs
- final control of packaged products
- quality control in food processing
- rapid characterization of the stability and polymorphic forms of drugs.

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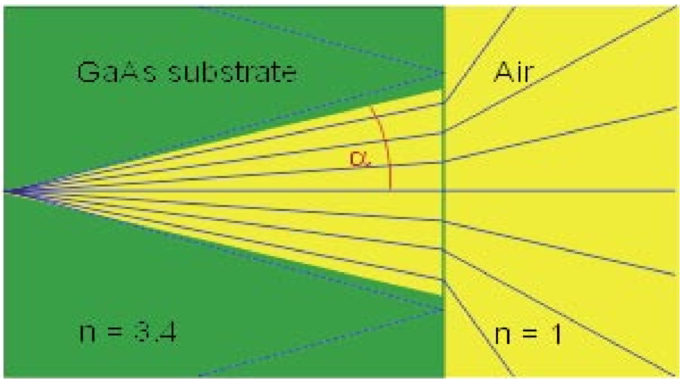
Substrate lens for PCA transmitter
PCA without substrate lens



Because of the high refractive index n ~ 3.4 of the semiconductor PCA the outgoing terahertz waves are strongly diffracted at the substrate-air interface. The boundary angle a or the total reflection can be calculated with

$$a = \arcsin(n^{-1}) \sim 17.1°$$

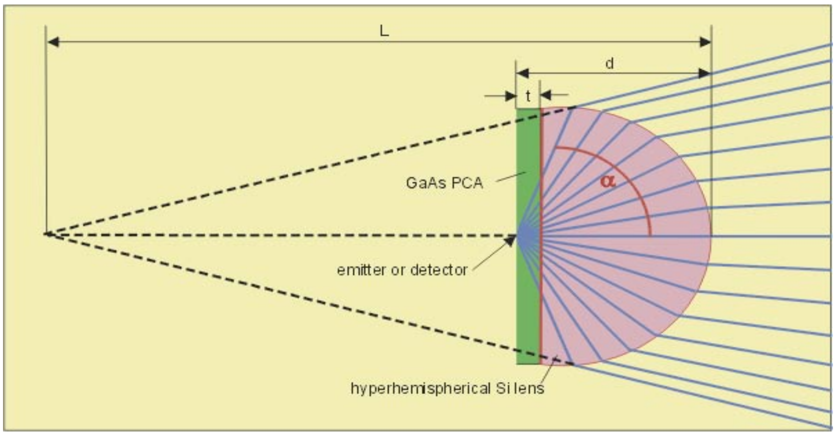
Only the THz waves emitted in the solid angle Ω with

$$\Omega = 4\pi \sin^2\frac{\alpha}{2} = 2\pi(1-\cos\alpha) = 2\pi\left(1-\sqrt{\frac{n^2-1}{n^2}}\right)$$

can escape the substrate. For GaAs with n = 3.4 the escape solid angle is Ω = 0.28. This is only 4.4% of the forward directed

Aplanatic hyperhemispherical lens

To increase the escape cone angle α , a hemispherical lens with the same refractive index n as the PCA can be used. To decrease the divergence in air, a hyperhemispherical lens with a certain distance d from the emitter to the tip of the lens is common. If this distance d is



$$d = r\left(\frac{n+1}{n}\right)$$

the hyperhemispherical lens is aplanatic, that means without spherical and coma aberration. For a silicon lens with almost the same refractive index n ~ 3.4 as GaAs at therahertz frequencies the distance is d = 1.29 r with the lens radius r. The height h of the aplanatic hyperhemispherical lens is therefore h = d - t with the thickness t of the semiconductor PCA.

The length L from the lens tip to the virtuell focus behind the lens is given by

$$L = r\,(n+1)$$

For silicon is L = 4.4 r. With this hyperhemispherical lens nearly all the forward directed terahertz intensity can escape the PCA. The problem left is the beam divergence, which requires a further focusing element like a lens or mirror.

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