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Resonant-cavity-enhanced devices improve efficiency

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High-speed RCE
photodetectors offer
low cost and high
performance for
short-distance optical communications and other applications.

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The design of a semiconductor photodetector necessarily combines an optical structure to efficiently capture the incident photons and an electrical structure to collect the photogenerated carriers. The optical and electrical designs are often inseparable, and thus a trade-off between individual performance parameters is required for the best overall performance. An important figure of merit for photodetectors used in optical communications is the bandwidth-efficiency product.

A large quantum efficiency--that is, the probability of detecting incident photons--is crucial for photodetectors. The quantum efficiency of conventional detector structures is governed by the absorption coefficient of the semiconductor material, meaning that thick active regions are required for high quantum efficiencies. Thick active regions, however, reduce device speeds because of the long transit times required. As a result, to optimize the gain-bandwidth product it is desirable to enhance quantum efficiency without increasing the active-layer thickness.

During the past decade, a new family of optoelectronic devices has emerged with performance that is enhanced by placing the active device structure inside a Fabry-Perot resonant microcavity (see "Evolution of resonant cavity enhancement," p. 16). In such structures, the device functions largely as before but is subject to the effects of the cavity--primarily wavelength selectivity and a large enhancement of the resonant optical field. Optoelectronic devices of this genre are typically referred to as resonant cavity enhanced (RCE).

The increased optical field allows photodetectors to be made thinner and, therefore, faster, while simultaneously increasing the quantum efficiency at the resonant wavelengths. Because off-resonance wavelengths are rejected by the cavity, the photodetectors exhibit both wavelength selectivity and high-speed response, making them ideal for optical communications.

The quantum efficiency h of a photodetector is defined as the probability that a single photon incident on the device generates an electron hole pair that contributes to the detector current. When many photons are present, which almost always is the case, quantum efficiency is defined as the current flux/photon flux ratio. The quantum efficiency depends on the absorption coefficient a and the thickness of the absorbing layer d.

For a high-speed photodiode, in which the depletion width is small, that is, ad1, with absorption occurring only in the depleted region, quantum efficiency is

The most important response-speed limitation in small-area photodiodes is the drift time across the depleted region. The transit time-limited 3-dB bandwidth of a thin detector is

ftr = 0.45(n/d), where n is the carrier velocity. Therefore, the bandwidth efficiency product for a thin detector with no capacitance limitation is obtained as

For AR coated (R = 0) gallium arsenide detectors (a @ 104 cm-1, nh = 6 ¥ 106 cm/s), this product is about 27 GHz.1

The quantum efficiency of thin photodetectors can be improved by collecting the light through the mesa edge of the device, perpendicular to the electrical current. This configuration provides simultaneously a long, albeit narrow, absorption region and a short current path, allowing the independent optimization of bandwidth and quantum efficiency. In this waveguide configuration, however, coupling the incident light into the waveguide represents a significant technological challenge, and the insertion loss of the incoming light limits the overall quantum efficiency (see Fig. 1).

Theory of RCE detection

Quantum efficiency of RCE photodetectors and its spectral dependence have been formulated in detail.2 For an RCE detector with cavity length L, an absorption region of thickness d, absorption coefficient a, and reflectivities of R1 and R2 for top and bottom mirrors, respectively, the quantum efficiency h can be expressed as

where y1 and y2 denote phase shifts due to light penetrating into the mirrors. Because the propagation constant b is a function of wavelength (b = 2n/l0, where l0 is the vacuum wavelength and n is the refractive index), h is a periodic function of the inverse wavelength, and it is enhanced periodically at the resonant wavelengths (see Fig. 2). The peak at the resonant wavelengths can be derived by imposing the resonant condition (2 = 2 m, m = 1,2,3 ..)

In contrast with conventional detectors, a high quantum efficiency can be obtained for thin absorption layers and the bandwidth-efficiency product is no longer limited by material parameters.3 The overall expected improvement in the bandwidth-efficiency product is nearly three times that for a gallium arsenide (GaAs) photodiode with a 10 ¥ 10-µm2 junction area.2

Design criteria for RCE photodetectors

The RCE structure is capable of operating over a large and continuous wavelength range, either by tuning within a material system or by moving to a complementary material system. The superior performance of the RCE photodetection scheme depends critically on the realization of a low-loss cavity. This requirement dictates that both the mirror and cavity material must be nonabsorbing at the detection wavelength and that the mirrors have high reflectivity.

The multiple mirror periods, each l/4 thick, have a combined thickness on the order of microns. Therefore, the materials composing the mirror must be well lattice-matched to avoid the introduction of defects into the active layer. To minimize the number of mirror periods--thereby simplifying growth and reducing the device series resistance--it is desirable to have as large a refractive index difference as possible between the mirror materials.

The active-layer material must have a smaller bandgap than the mirror and cavity materials, but not so much smaller that large heterojunction-band offsets hinder the extraction of photogenerated carriers. The active layer absorption coefficient should be moderate (that is,

1 ¥ 103 a 5 ¥ 104 cm-1) within the operation spectrum to benefit from RCE effect. Various binary and ternary

compound semiconductors (such as a GaAs/(aluminum, indium) GaAs material system) grown by molecular-beam epitaxy allow for bandgap engineering in the design of novel RCE structures. The spectrum of RCE photodetectors covers from ultraviolet to infrared with the available semiconductor materials.

High-speed RCE Schottky photodiodes

Resonant-cavity-enhanced detection is particularly attractive for Schottky-type photodetectors because a semitransparent metal contact can also function as the top reflector (see figure on p. 15). Recently, we have demonstrated very high-speed RCE Schottky photodetectors operating at 900 nm.4 At this wavelength, a thin pseudomorphic indium gallium arsenide (InGaAs) layer serves as the absorption region in a cavity formed by a GaAs/AlAs distributed Bragg reflector and GaAs contact regions. Devices were fabricated by standard photolithography with mesa isolation and a gold air-bridge connecting the top contact to a coplanar transmission line designed for on-wafer microwave characterization.

High-speed measurements were made using a picosecond mode-locked Ti:sapphire laser tuned to the resonant wavelength. The devices were illuminated using a single-mode fiber on a microwave probe station, and the resulting pulses were observed on a 50-GHz sampling scope (see Fig. 3). The measured pulsewidth (Tmeas = 10 ps) can be approximated as

which is very accurate for Gaussian pulses and a good approximation for the actual measurements. Considering a 9-ps FWHM pulse for the 50-GHz scope and laser pulsewidth of 1.2 ps, the device speed was estimated to be 4.1 ps, corresponding to a bandwidth of

100 GHz.4 This is a conservative estimate because the microwave components and laser timing jitter also contribute to the measured pulse width.

The peak quantum efficiency is calculated as hmax = 70% for these RCE Schottky photodiodes, and experimental results yielded as high as 50% for similar structures. Combined with the high-speed results, the bandwidth-efficiency product exceeds 50 GHz.

We are currently pursuing GaAs RCE Schottky photodiodes working at 850 nm to complement the high-performance vertical-cavity surface-emitting lasers for short-distance optical communications. Similar principles apply for 1.3- and

1.55-µm wavelength ranges. In the case of integrated optics, high-speed RCE detectors will have less of an impact because waveguide photodetectors are more suitable and provide very high bandwidth. The impact of high-speed RCE detectors will be in applications where a top-illuminated, low-cost, high-performance detector is desirable. o

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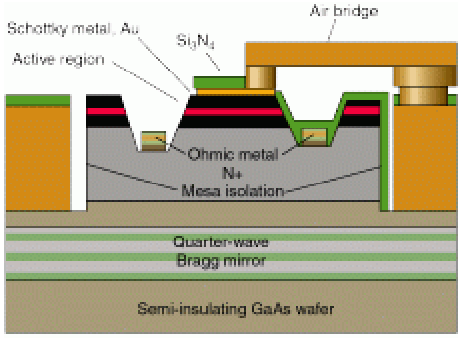
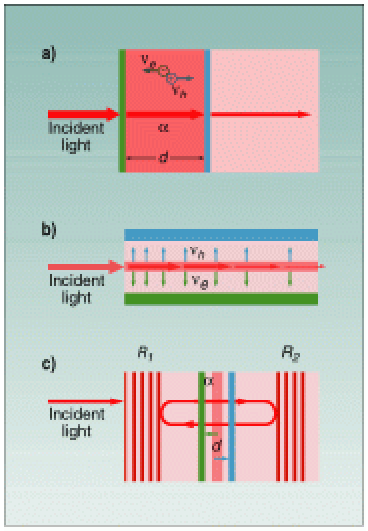


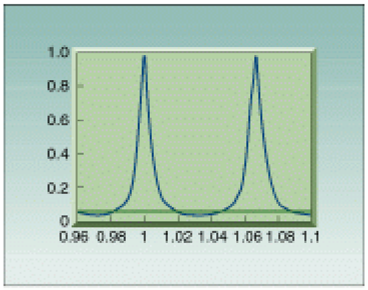
3DS-1 Frontis

Resonant-cavity-enhanced Schottky photodiodes are fabricated using molecular-beam epitaxy and standard photolithography to produce Fabry-Perot low-loss microcavities.



3DS-1 Fig. 1

FIGURE 1. In top-illuminated (a) and resonant-cavity-enhanced detectors (b), the light propagation and carrier collection is in the same axis. In waveguide detectors (c), the carrier-collection direction is transverse to light propagation.



3DS-1 Fig. 2

FIGURE 2. Quantum efficiency of resonant-cavity-enhanced detectors has a periodic wavelength dependence. At resonance, the efficiency is strongly enhanced.

Histogram is enabled...

FIGURE 3. Measured temporal response of the RCE Schottky photodiode shows a FWHM of 10 ps; measurement is limited by the scope response.

Evolution of resonant cavity enhancement

In the last years of the 19th century, two French scientists, Alfred Perot and Charles Fabry, described a novel optical-interference device consisting of two thinly silvered glass plates placed in parallel. The interference caused by multiple reflections had in fact been analyzed theoretically by George Airy more than 60 years earlier. By the early 20th century, interference in a Fabry-Perot resonator had become a well-established phenomenon and widely used in spectroscopic measurements.

Over the many decades since the invention of the Fabry-Perot resonator, numerous applications in a variety of fields such as atomic spectroscopy, astronomy, metrology, optical bistability, velocimetry, and infrared sensors have emerged. Quite possibly, one of the most important applications of these resonators has been in active optical devices. Hence, the optical feedback in lasers is achieved by placing the active medium in a Fabry-Perot resonator.

While the fundamental physics of resonant-cavity-enhanced (RCE) devices has been known for nearly 100 years, and the first observation of resonant cavity enhancement in semiconductor devices occurred more than 20 years ago, recent developments have stimulated research activity in this area.

With the advent of fiberoptic components and systems, there is an increasing demand for very-high-bandwidth photonic devices in modern optical communication networks. New crystal-growth techniques such as molecular-beam epitaxy provide researchers with the capability of producing epitaxial Fabry-Perot microcavities within exacting specifications allowing realization of RCE devices. Recently, RCE photodetectors have been pursued by several research groups toward high-speed applications.

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