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An ultra fast quantum well infrared photodetector

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Abstract

Quantum well infrared photodetectors (QWIP) are intrinsically very high speed devices that usually are limited in response speed by the external circuitry. An ultra fast QWIP has been developed that integrates a QWIP mesa with an integrated co-planar waveguide to cable transition. Devices packaged with both K connectors and V connectors have been assembled and tested. At DC the devices demonstrate optical heterodyne efficiency of 90% or greater. Optical heterodyne measurements using CO_2 lasers have shown that with a K connector, response is flat ±10% up to 40 GHz and then drops rapidly due to the cable. Using a V connector, heterodyne efficiency of 50% of ideal has been measured at 56 GHz and 25% at 74 GHz.

Keywords: Quantum well; Photodetector

1. Introduction

It has been known for some time that QWIPs have a carrier lifetime of a few picoseconds which is the enabling physics for a device with a bandwidth of at least 40 GHz. Liu et al. demonstrated heterodyne detection at 82 GHz using free space coupling to a horn antenna [1]. Steinkogler et al. demonstrated fast pulse detection in their studies of electron transport in QWIPs [2,3]. The microwave connection for their work was made by a probe that made contact directly on the mesa. The high speed response of QWIPs in combination with high infrared absorption and low noise-equivalent power make them well suited for a number of applications where fast IR response is required [4].

However, in applications where the QWIP is used as a sensor it is very inconvenient to use a probe. For practical application, devices must be mounted in packages and make use of electrical cables and connectors. In earlier work we mounted QWIPs by wirebonding to a microstrip launcher [5]. The device bandwidth was limited by parasitics to about 12 GHz. This is the widest bandwidth mid-infrared detector that has been assembled into a package and provided with a cable connector. It

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has been used for a number of applications and demonstrations. It was used as a heterodyne detector in plasma diagnostics for the JT-60U tokamak [6]. In that application a bandwidth of 8 GHz was sufficient. However, there are applications which demand more of the intrinsic speed available from a QWIP.

Paiella et al. have used a 12 GHz QWIP to investigate high speed pulse generation using a quantum cascade laser (QCL) [7]. In that work it was found that the QCL was capable of generating 45 ps pulse widths which exceeded the 12 GHz bandwidth of the QWIP used. However, using optical techniques, pulse widths estimated to be 5.4 ps have been generated using a mode locked QCL [8]. Applications that exploit the very high speed potential of QCLs and QWIPs are under investigation. Experimental optical telecommunications links have been demonstrated using 8 μm wavelengths and have provided about 7 GHz bandwidths [9,10]. There is now a need for much wider bandwidth QWIPs.

The objective of this project is to develop an ultra fast QWIP that exploits the intrinsic speed demonstrated by Steinkogler et al. while packaged with a co-axial cable connector.

2. Design

We start with the QWIP electrical model given by Liu et al. [5]. For a photocurrent i_q and cable impedance R_L the power available at frequency ω is the product of two factors $\alpha \cdot \beta$,

$$P = \alpha(\omega) \cdot \beta(\omega) \cdot i_q^2 \cdot R_L, \tag{1}$$

where $\alpha(\omega)$ is due to the photoconductive lifetime and $\beta(\omega)$ models the circuit response. The frequency dependence induced by the photoconductive lifetime τ is given as

$$\alpha(\omega) = \frac{1}{1 + (\omega\tau)^2}. \tag{2}$$

The circuit limited response is given as

$$\beta(\omega) = \frac{8}{(1 - \omega^2 LC)^2 + \omega^2 \left(R_L C + \frac{L}{R_L}\right)^2}, \tag{3}$$

where L is the wire bond inductance and C the QWIP capacitance.

A consequence of these 2 factors is that at high frequencies the power produced by the QWIP decreases in proportion to $1/\omega^6$. The photoconductive lifetime is a property of the semiconductor physics while the circuit is a property of the device geometry. Our objective in this work is to develop a device geometry which will allow the high frequency response to reach a level limited only by the semiconductor physics. To do that, we eliminate parasitic elements and make the characteristic frequencies in Eq. (3) greater than $1/\tau$. The high frequency response (defined as $\omega > 1/\tau$) will then be proportional to $1/\omega^2$.

The parasitic inductance will be reduced by eliminating the wire bond and using a micro-fabricated air bridge to make contact to the top of the QWIP mesa. The capacitance will be reduced by making the QWIP smaller. The electrical connection from the QWIP to a coaxial cable will be made using a 50 Ω transmission line fabricated on the GaAs wafer.

2.1. QWIP capacitance

A 100 well QWIP optimized for high absorption and high operating temperature was selected as the basic layer structure [11]. The layer system has wells of 6.6 nm width with barriers of 25 nm. The combined thickness of 100 wells is $h = 3160$ nm. For small signals, the electrical model of the QWIP is a small capacitor in parallel with a shunt conductance and the photocurrent source. For high frequency considerations, the shunt conductance can be ignored when the temperature is below about 200 K. The capacitance is $C = \epsilon_0 \epsilon_r A/h$.

An elegant electronic design is to use a transimpedance amplifier to decouple the QWIP from the cable. If the amplifier has sufficient bandwidth it can provide a frequency response limited only by the carrier lifetime. However, integrating an amplifier with our QWIP process requires a substantial increase in fabrication complexity. It has been found that connecting the QWIP directly to the cable has few electronic disadvantages. However, the 1/RC frequency cannot be arbitrarily increased by reducing the device area since the area also