CONF-891205--2

UCRL--101579

DE90 003452

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This paper is being prepared for submittal to the International Electronic Devices Meeting
Washington D.C.
December 3 thru 6, 1989

November 1989

Lawrence Livermore National Laboratory

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ABSTRACT

This paper presents a concept where improved responsivity for picosecond photoconductors is achieved by utilizing a graded bandgap $Al_xGa_{1-x}As$ active detecting layer grown on a high defect density, low temperature GaAs layer by MBE. By taking advantage of the superior transport properties of the graded $Al_xGa_{1-x}As$ layer, order of magnitude improvement in responsivity has been demontrated, along with 2–6 times improvement in peak photocurrent response.

INTRODUCTION

For optoelectronic system applications where incident radiative power density is limited, the critical issue becomes the determination of an appropriate photodetector which provides the desired responsivity without degrading the overall system bandwidth. Considering PIN photodiodes, if it is required to increase the area of the detector in order to collect more incident radiation, the response speed becomes limited by the capacitance of the device. Ultimately, both the bandwidth and the amplitude of the photocurrent are determined by the thickness of the intrinsic layer. Photoconductive devices have achieved picosecond photoresponses by the introduction of suitable recombination centers to the semiconductor lattice structure (1,2). Consequently, these defects behave as scattering centers which degrade the carrier mobility, hence drift velocity, of the material, thereby limiting the responsivity. Recently, picosecond photoconductivity has been demonstrated in MBE GaAs by introducing point defects to the crystal lattice during epitaxial growth at low substrate temperatures (3). This material is reported to have the highest carrier mobility of any semiconductor which has achieved picosecond responses. Yet, the scattering limited mobility of the low temperature (LT) GaAs layer is such that photodetectors made from this material will be application limited. Therefore, a higher performance photoconductive device, using a low defect density, bandgap graded detecting region, has been investigated for picosecond pulsing and sampling applications.

THEORETICAL CONCEPT

Since the lattice of the LT GaAs layer maintains its crystalline characteristics, epitaxial layers suitable for active GaAs devices can be grown on the LT buffer layer (4,5). With this capability, a photodetector structure which utilizes a high mobility active detecting region, yet takes advantage of a highly defective layer to facilitate picosecond recombination, can be realized. The basic concept which has been investigated is illustrated in Fig. 1. A LT GaAs buffer layer is grown on a SI GaAs substrate by MBE at a growth temperature of 300°C using Ga and As_4 beam fluxes. The resulting LT buffer is approximately 1.75 μm thick. Previous characterization of LT GaAs layers has demonstrated carrier lifetimes on the order of ~2ps, with a corresponding effective or combined mobility of μ_{eff}~150-200cm²/v-s (3). These properties are a result of the excessive amount of point defects created by the low temperature epitaxial growth under As-rich conditions. A graded $Al_xGa_{1-x}As$ layer, which is the active detecting region, is grown on the LT GaAs buffer. Planar electrodes on the surface form the photoconductive gap, as illustrated in Fig. 2. For the AlGaAs/GaAs materials system, the conduction and valence band offsets are such that the bandgap graded structure provides intrinsic, quasi-electric fields which transport photogenerated electrons and holes in the same direction. For this structure, the charge is swept vertically toward the LT GaAs buffer layer. The quasi-electric fields are described by

$$q\vec{\varepsilon}_n = dE_c/dx \qquad (1)$$

$$q\vec{\varepsilon}_p = dE_v/dx \qquad (2)$$

For a bandgap gradient over a distance L, the electron and hole velocities are described as

$$\vec{v}_n = \langle\mu_n(x, |\vec{\varepsilon}_n|)\rangle \cdot \vec{\varepsilon}_n = \langle\mu_n(x, |\vec{\varepsilon}_n|)\rangle \cdot \Delta E_c/qL \qquad (3)$$

and

$$\vec{v}_p = \langle\mu_p(x, |\vec{\varepsilon}_p|)\rangle \cdot \vec{\varepsilon}_p = \langle\mu_p(x, |\vec{\varepsilon}_p|)\rangle \cdot \Delta E_v/qL \qquad (4)$$

respectively. The brackets around the mobility account for the fact that the mobility depends on Al fraction, thus is averaged over the graded structure. The current continuity equations can now be approximated

$$dn/dt = d(J_n/q)/dx - R = n\vec{v}_n/L - n/\tau_n \qquad (5)$$

$$dp/dt = d(J_p/q)/dx - R = p\vec{v}_p/L - p/\tau_p \qquad (6)$$

where τ_n and τ_p are the electron and hole lifetimes. Solving these equations determines the appropriate time constant for the photogenerated electrons and holes

$$n(t) = n(0)\exp(-t\cdot(\vec{v}_n/L + 1/\tau_n)) \qquad (7)$$

$$p(t) = p(0)\exp(-t\cdot(\vec{v}_p/L + 1/\tau_p)) \qquad (8)$$

From this analysis, the speed of response for this detector structure will depend on the time it takes to sweep the photogenerated electrons and holes from the graded $Al_xGa_{1-x}As$ region and

*Work done under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W–7405–ENG–48.

subsequently recombine in the LT GaAs layer. Therefore, a higher responsivity is achievable by absorbing the incident optical energy within the high mobility graded bandgap region.

MODEL RESULTS

Utilizing the formalism developed above, calculations of the photocurrent transient response can be conducted. Three cases were investigated to coincide with experimental devices. The first is that simply for the LT GaAs layer, with both electron and hole lifetimes of 1.6ps, and carrier mobilities, μ_n=150 cm^2/V-s and μ_p=50 cm^2/V-s. The other examples are a 2000 Å layer graded from AlAs to GaAs, and a 4000 Å layer graded from $Al_{.7}Ga_{.3}As$ to GaAs, both with near linear gradients, grown on top of the LT GaAs layer. The formulations developed by (6), (7), and (5) were assumed in determining the energy band offsets, low field mobility, and electric field dependent mobility respectively for the graded bandgap region. The carrier lifetime in the AlGaAs layer was assumed to be >1ns, therefore recombination is negligible in this layer. The incident optical pulse was assumed to be Gaussian shaped, 9 ps FWHM, with a peak power of 10 W. The wavelength is 532 nm, and the corresponding absorption depth (1/e) is d_e~1000 Å. The gap length of the photoconductor is 15 μm, with a bias voltage of 5 V. Using the above parameters in the calculations, the continuity equations are solved along with Poisson's equation in conjunction with the circuit equations assuming a 50 Ω load resistance. A uniform electric field is assumed across the photoconductive gap for this analysis. The results are shown in Fig. 3 for the device structures modeled. It is observed that the detector output response can be increased by three to four times, while retaining response times of 10–20 ps FWHM. The structure with the 4000 Å graded layer has a higher responsivity as a result of the increase in mobility for decreased Al content, along with greater absorption of the incident power over the thicker graded layer. It is also evident from this analysis that long tails can exist as a result of the lower electric field present as the bandgap gradient is reduced. This problem is of particular importance for the hole transport properties, since the valence band offset is small compared to the conduction band offset for this materials system.

EXPERIMENTAL RESULTS

The three photoconductive device structures previously described were fabricated. The graded $Al_xGa_{1-x}As$ layers were grown on the LT GaAs buffer at a substrate temperature of 600°C. Ohmic metal, consisting of 250 Å AuGe, 50 Å Ni, 3000 Å Au was then deposited. Electrodes were formed using a standard liftoff technique, with a photoconductive gap length of 15 μm formed within a 100 μm wide transmission line structure. Photoconductive gaps are placed along the transmission line to sample the waveform as it propagates. In this manner, the autocorrelation response of the photoconductor is measured. The autocorrelation response measured for photoconductors fabricated from the LT GaAs buffer, the 2000 Å, and the 4000 Å graded $Al_xGa_{1-x}As$ layers are illustrated in Fig. 4 a, b, and c, respectively. The optical source is a Nd:YAG laser with a fiber optic pulse compressor, which is frequency doubled to produce a 8–10 ps FWHM optical pulse at a wavelength of 532 nm. Deconvolving the autocorrelation responses, the photocurrent responses exhibit 10 ps, 11 ps, and 24 ps FWHM for the three structures. The amplitude of the photoresponse can be determined using a sampling oscilloscope, which is limited to ~35 ps FWHM response times. The actual amplitude is determined from that measured with the oscilloscope under the assumptions of charge conservation and response time as measured by autocorrelation. With a 5 V bias and 78 pJ of incident energy, the output responses of the three photoconductor structures into a 50 Ω load were determined to be 57 mV, 165 mV, and 292 mV. These results demonstrate good agreement with the previous calculations. The average photocurrent-voltage characteristics for the three structures are illustrated in Fig. 5. From this, it is observed that not only can the peak output current be increased by factors of 2–6, but the responsivity of the photoconductive device can be increased by an order of magnitude by utilizing these graded bandgap structures. To demonstrate the large signal pulsing capability, Fig. 6 illustrates the response of the 2000 Å graded $Al_xGa_{1-x}As$ photoconductor with 40 V bias, and ~230 pJ of incident energy. This response, which is limited by the mounting fixture to ~60 ps FWHM, represents an on-chip signal of 3.8 V, 11 ps FWHM.

CONCLUSIONS

A photoconductive device concept has been presented which allows for improved performance over traditional picosecond photoconductors. A methodology has been introduced which provides a capability to design photodetector speeds into the <10 ps regime, while obtaining responsivity improvements greater than an order of magnitude over present photoconductive device technology. Application of this concept to alternate material systems will allow for high performance picosecond photodetectors in the 0.8-1.6 μm wavelength range.

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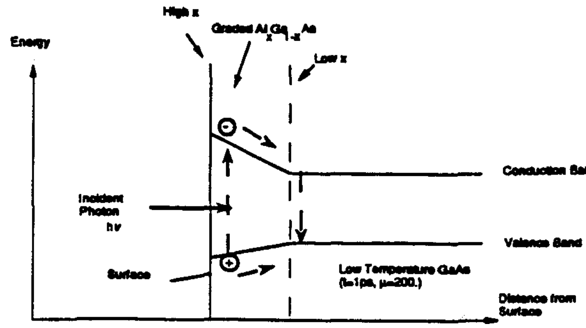

Figure 1. Energy band diagram illustrating purpose of graded bandgap $Al_xGa_{1-x}As$ detecting region.

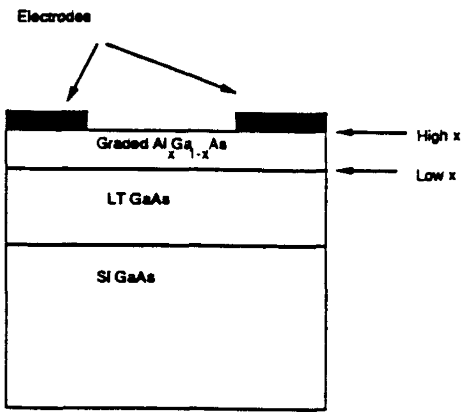

Figure 2. Photoconductive device structure using bandgap graded layer on LT GaAs buffer layer.

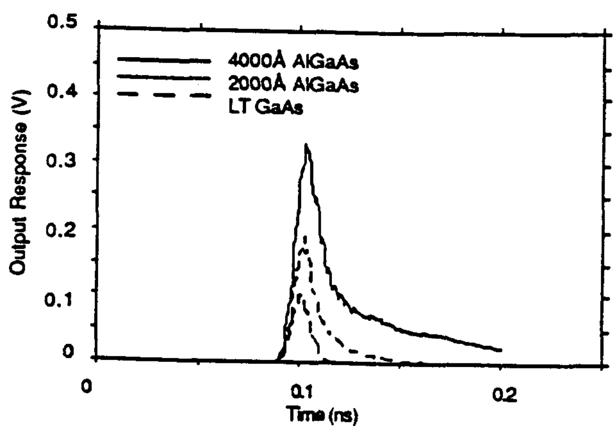

Figure 3. Calculated photoresponse of LT GaAs, 2000 Å, and 4000 Å graded $Al_xGa_{1-x}As$ photoconductive devices with 9ps FWHM, 10 W peak power, 532 nm optical pulse.

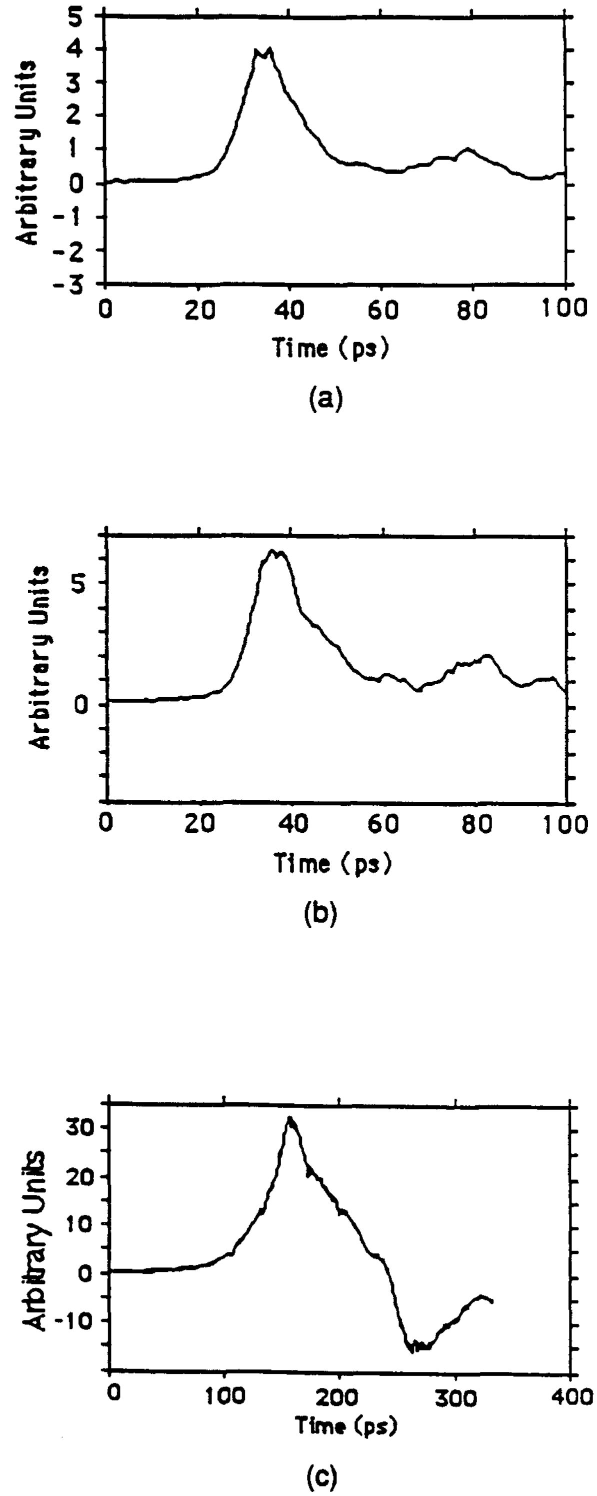

Figure 4. Autocorrelation response of a) LT GaAs, b.) 2000 Å graded $Al_xGa_{1-x}As$, and c.) 4000 Å graded $Al_xGa_{1-x}As$ photoconductive devices measured with 8–10 ps FWHM, 532 nm optical pulse.

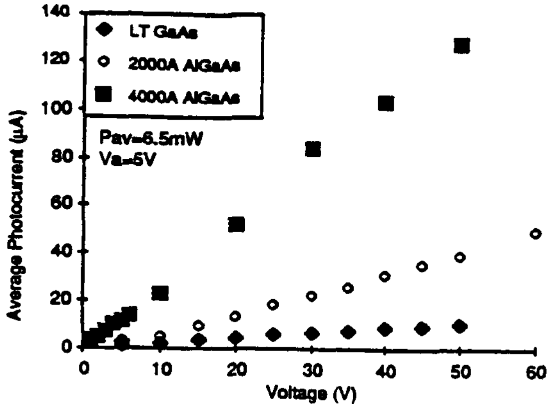

Figure 5. Measured photocurrent-voltage characteristics.

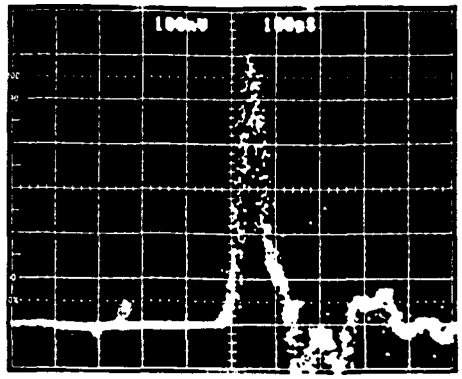

Figure 6. Sampling oscilloscope trace of output response for 2000 Å graded $Al_xGa_{1-x}As$ photoconductor with 40 V bias and 230 pJ incident energy.