as the bottom contact to the thinned n^+-Si substrate. The lasers were evaluated at room temperature under pulsed operation. For a 170×240 μm device, a threshold current density as low as 3.3 kA/cm^2, the lowest ever reported for GaAs lasers grown on Si, was obtained despite the fact that the active region is only 3.1 μm away from the Si interface. No evidence of abnormal turn-on delay was seen for pulses as short as 10 ns. Steady single longitudinal mode oscillation was observed up to 1.3 times threshold current, indicating the superiority of the MQW heterostructures and the growth techniques employed here, as compared with previously published results. Initial measurements on 10-μm-wide stripe lasers show threshold below 250 mA, and similarly clean, single mode emission spectra. We are also presently studying the fast pulse response of these lasers as well as their CW operation.

This work was supported by the National Science Foundation under Grant ECS 84-13178.

[1] T. H. Windhorn *et al.*, *Appl. Phys. Lett.*, vol. 47, p. 1031, 1985.
[2] R. Fischer *et al.*, *Appl. Phys. Lett.*, vol. 38, p. 1360, 1986.

VB-6 Continuous Room-Temperature Laser Operation of $Al_xGa_{1-x}As$–GaAs Quantum Well Heterostructures Grown on Si—D. G. Deppe, N. Holonyak, Jr., D. W. Nam, K. C. Hsieh, and R. W. Kaliski, Electrical Engineering Research Laboratory, University of Illinois at Urbana-Champaign, 1406 W. Green St., Urbana, IL 61801, R. J. Matyi, J. W. Lee,[1] and H. Shichijo, Central Research Laboratory, Texas Instruments, Dallas, TX 75265, and J. E. Epler, R. D. Burnham,[2], H. F. Chung, and T. L. Paoli, Xerox Palo Alto Research Center, Palo Alto, CA 94304.

Strained-layer GaAs grown epitaxially on Si substrates has attracted considerable attention because of the possibility of solving the problem of large-scale GaAs "substrate" availability, as well as the possibility of mixing GaAs integrated circuits (IC's) with Si IC's. Initial results indicate that this technology, to the extent that it is possible, is easier for majority-carrier devices and harder for optoelectronic devices. A test of the latter is that of laser operation. Recently we have described room temperature *continuous* (CW) photopumped laser operation of a four-well $Al_xGa_{1-x}As$–GaAs quantum well heterostructure (QWH) grown by metalorganic chemical vapor deposition (MOCVD) on a GaAs layer grown first on Si by molecular beam epitaxy (MBE) [1]. Unfortunately, however, the defect densities and laser thresholds are so high (7×10^4 W/cm^2, $J_{eq} = 2.9 \times 10^4$ A/cm^2 that the CW laser operation is short lived (minutes). The problem with mismatch defects (dislocations) can be reduced presumably by improvements in the crystal growth and, in addition, by better QW layer choices and arrangements, e.g., a single well that collects carriers efficiently but has only two heteroboundaries subtending dislocations. In this report we present data demonstrating *stable room-temperature continuous* (CW) photopumped laser operation of a single-well $Al_xGa_{1-x}As$-GaAs QWH grown on Si by a combination of MBE and MOCVD. The CW 300-K laser operation of the single-well $Al_xGa_{1-x}As$-GaAs QWH occurs at an excitation threshold of 6.7×10^3 W/cm^2 ($J_{eq} = 2.8 \times 10^3$ A/cm^2), or a factor of ten lower than similar multiple-well QWH's. The laser operation is stable for 4 h (or more), the length of the "test" (which is truncated to save our Ar$^+$ laser). These results indicate that CW 300-K p-n diode QWH lasers can be grown and fabricated on Si, which indeed is the case [2] and will be described. In addition to a description of the CW 300-K QWH laser operation (photopumped samples and diodes), we show (via TEM micrographs) the nature of the dislocations from the Si substrate on up to the active region of the QWH.

[1]Now at Kopin Corp.
[2]Now at Amoco.

[1] R. W. Kaliski, N. Holonyak, Jr., K. C. Hsieh, D. W. Nam, J. W. Lee, H. Shichijo, R. D. Burnham, J. E. Epler, and H. F. Chung, *Appl. Phys. Lett.*, vol. 50, pp. 836–868, Mar. 20, 1987.
[2] D. G. Deppe, N. Holonyak, Jr., D. W. Nam, K. C. Hsieh, R. J. Matyi, H. Shichijo, J. E. Epler, and H. F. Chung, "Room temperature continuous operation of p-n $Al_xGa_{1-x}As$-GaAs quantum well heterostructure lasers grown on Si," unpublished.

VB-7 InP/InGaAsP/InGaAs Avalanche Photodiodes Grown by Chemical-Beam Epitaxy—J. C. Campbell, W. T. Tsang, G. J. Qua, and B. C. Johnson, AT&T Bell Laboratories, Holmdel, NJ 07733.

We report the first demonstration of InP/InGaAsP/InGaAs avalanche photodiodes (APD's) grown by chemical-beam epitaxy (CBE). These APD's exhibit low dark currents and very high bandwidths.

For long-haul lightwave transmission systems operating at high bit rates, APD's provide a significant margin in receiver sensitivity compared to p-i-n photodiodes. To date, the most promising APD structure for this application consists of an InP multiplication region and an $In_{0.53}Ga_{0.47}As$ absorbing layer separated by a transition region of one or more intermediate-bandgap layers of InGaAsP. In order to achieve high avalanche gain, low dark current, and adequate bandwidth, the thicknesses and carrier concentrations of the epitaxial layers must be maintained within very narrow tolerances. This is difficult to achieve by liquid-phase epitaxy (LPE). In addition, LPE is not as suitable for large-scale production as other growth techniques such as hydride or halide vapor-phase deposition (VPE), metalorganic chemical vapor deposition (MOCVD), or molecular-beam epitaxy (MBE). Previously, InP/InGaAsP photodetectors grown by MOCVD or MBE have exhibited high dark currents due to the difficulty of achieving low bandground carrier concentrations and interfaces with low defect densities. Recently, InP/InGaAsP/InGaAs APDs grown by MOCVD have been demonstrated [1]. Those APDs exhibited bandwidths less than 1.5 GHz. With the CBE-grown InP/InGaAsP/InGaAs APD's described in this paper, bandwidths as high as 6 GHz in the low-gain regime ($M < 4$) were achieved. This is comparable to the highest bandwidth reported to data for this type of APD [2]. For higher multiplication values, a gain-bandwidth-limited response was observed; the gain-bandwidth product was in the range 25 to 30 GHz. The frequency response of these APD's will be explained in terms of five effects: carrier diffusion, the transit time through the depletion region, the *RC* time constant, charge accumulation at the heterojunction interfaces, and the avalanche buildup time. For example, in order to minimize hole trapping at the heterojunction interfaces we incorporated, for the first time, three thin (≤ 700 Å) InGaAsP ($E_g = 1.13$, 0.95, and 0.80 eV) transition layers.

The other device parameters can be summarized as follows: The total dark current was as low as 3.6 nA at 90 percent of breakdown and the primary multiplied dark current was 1.5 nA. Useful avalanche gains as high as 30 were achieved. The quantum efficiency of uncoated devices at 1.3 μm was approximately 55 percent. The device capacitance (diameter = 40 μm) was <0.1 pF at the operating voltage.

[1] R. D. Dupuis, J. R. Velebir, J. C. Campbell, and G. J. Qua, *Electron. Lett.*, vol. 22, p. 235, 1986.
[2] J. C. Campbell, W. S. Holden, J. F. Ferguson, A. G. Dentai, and Y. K. Jhee, 5th Int. Conf. Integrated Opt. and Opt. Fiber Comm., Venice, Italy, 1985.

VB-8 Distributed Feedback Surface Emitting Laser Diode with Lateral Buried Heterostructure—Mutsuo Ogura,[1] Wei Hsin, S. C. Wang,[2] Jane J. Yang,[3] Shih-Yuan Wang,[4] Yu-Min Houng,[4] Ming-Chiang Wu, John R. Whinnery, and Shyh Wang, Department of Electrical Engineering and Computer Sciences, and Electronics Research Laboratory, University of California, Berkeley, CA 94720.

Threshold current of 2 mA at room temperature CW operation is realized in a distributed feedback surface emitting laser diode (DFB-SELD) with lateral buried heterostructure (LBH). In this LBH structure, the active region (GaAs part of the AlGaAs/GaAs multilayer) is entirely surrounded with N- and P-type AlGaAs cladding layers which are formed by selective liquid phase epitaxy and zinc diffusion techniques. The light emitting region is tightly confined inside of the multilayer and the carrier confinement is very effective. The I-L characteristic has a clear threshold at 2 mA. The light output is 28 μW at 10 mA, dc. The far field pattern is almost circular. Beam angle is 7 degrees. Sharp luminescence peak begins to show up at 882 nm at the drive current of 1–2 mA. Therefore, lasing action at very low threshold current is confirmed. However, the lasing spectrum is broad (2–3 nm) and there is large satellite emission at shorter wavelengths. Further improvement in the lasing spectrum is expected with proper modification of the optical cavity. This DFB-SELD is very advantageous for electro-optic integration because it does not need cleavage nor substrate etching process to form a vertical optical cavity.

[1]Also with Electrotechnical Laboratory, Sakuramura , Niihari-gun, Ibaraki 305, Japan.

[2]Lockheed Missiles and Space Company, Inc., Palo Alto, CA 94304-1187.

[3]Space and Technology Group, TRW, One Space Park, Redondo Beach, CA 90278.

[4]Hewlett-Packard Laboratory, Palo Alto, CA 94303-1181.

VIA-1 The Switching Mechanism in the Heterostructure Hot-Electron Diode

—T. K. Higman, J. M. Higman, M. A. Emanuel, K. Hess, J. J. Coleman, and J. Kolodzey, Coordinated Science Laboratory and NSF Engineering Research Center for Compound Semiconductor Microelectronics, University of Illinois at Urbana-Champaign.

A new two-terminal device [1], the heterostructure hot-electron diode (H^2ED) which shows S-shaped negative differential resistance (NDR) and the capability of generating microwave oscillation will be reported. In this new structure two possible conduction mechanisms exist. At low fields, the current is limited by tunneling through a wide-bandgap heterostructure barrier, resulting in a relatively large device series resistance. At higher fields, electrons are heated to sufficient energies so that thermionic emission over the barrier becomes dominant and the series resistance in this region becomes negligible. Since the energy distribution of electrons is confined to a narrow range of energies, one or the other of these modes will dominate conduction. The transition between these current conduction modes is shown to result in a negative differential resistance (NDR) and switching speeds that may be extremely fast. In this paper we present the results of investigations of the H^2ED, both theoretical and experimental, which verify the proposed mechanism and determine more precisely the underlying physical phenomena involved. We show, using an analytic theory, that the field switching mechanism previously proposed is consistent with the NDR observed in the H^2ED. In addition to the tunneling and thermionic emission of hot electrons, the accumulation of electrons at the heterointerface is identified as an important mechanism in the operation of the device. AlGaAs–GaAs structures were grown by MOCVD with a wide variation of layer thicknesses and compositions. The S-shaped NDR was observed, to varying degrees, in many different structures. Experimentally, we verify that the basic physical requirements for switching predicted by the theory are correct and further we show that the potentially detrimental effect of impact ionization can be minimized by proper design. Numerical solutions (dc) and experimental current–voltage results are found to be in good agreement. Test fixture limited broadband gain to 18 GHz has been observed in these devices and will be described. These results indicate that the H^2ED should be capable of transit time limited high-speed performance.

[1] K. Hess, T. K. Higman, M. A. Emanuel, and J. J. Coleman, *J. Appl. Phys.*, vol. 60, p. 3775, 1986.

VIA-2 Fundamental Oscillations up to 200 GHz in a Resonant-Tunneling Diode

—E. R. Brown, T. C. L. G. Sollner, W. D. Goodhue, and C. D. Parker, Lincoln Laboratory, Massachusetts Institute of Technology.

We report the observation of fundamental oscillations up to 200 GHz in a double-barrier diode (DBD) at room temperature. The physical basis for these oscillations is the negative dynamic conductance (NDC) associated with the resonant tunneling of electrons through a quantum well bounded by two tunnel barriers. A key to achieving the present results was the use of thin (1.5 nm) AlAs barriers and moderate doping ($N_D = 2 \times 10^7$ cm^{-3}) in the n-GaAs outside the barriers. The thinness of the AlAs barriers compensates for the relatively large Γ-point conduction-band offset (~ 1.0 eV) to yield high peak current density (4×10^4 A $\cdot$ cm^{-2}) and, more importantly, a peak-to-valley ratio of about 3.5 : 1 at room temperature. The moderate doping provides a depletion layer at resonance which is long enough to reduce the device specific capacitance, but short enough to make the transit-time delay negligible.

Another key to these results was the development of rectangular-waveguide resonators capable of providing greater-than-unity circuit Q at frequencies where the terminal negative resistance of the diode is rapidly aproaching zero. The diodes were mounted in the gap between the waveguide floor and the bottom of a post that protruded roughly half-way into the guide. The contact to the individual diodes was made with a whisker whose length (~ 0.18 mm) was as short as practically possible to minimize parasitic inductance in the circuit. A WR-6 resonator yielded oscillations between 102 and 112 GHz with peak power of about 5 μW in this band. The frequency tuning was accomplished primarily with bias voltage. A scaled-down version of this resonator in WR-3 waveguide achieved oscillations between 192 and 201 GHz, again tunable mostly by bias voltage. The peak power in this range was about 0.2 μW.

The results described above were obtained with diodes from the same wafer, and provide a continuous curve of power versus frequency, starting at the point 200 μW, 20 GHz. Although the curve falls rapidly at the high-frequency end, it is clear that f_{MAX} (the frequency above which the real part of the terminal impedance is positive) for this wafer is higher than our previous conservative estimate, $f_{MAX} = 187$ GHz. There is some uncertainty in all of the parameters used to calculate f_{MAX}, i.e., the series resistance, the maximum NDC (G_{MAX}) and the capacitance which shunts G_{MAX}. The greatest uncertainty occurs in the value of G_{MAX} since the measured current–voltage curve is distorted by self-detection of the oscillations. A somewhat more optimistic value of G_{MAX}, which remains consistent with all observations and theory, yields $f_{MAX} = 280$ GHz. This would increase to about 400 GHz for a wafer having a specific contact resistance of 10^{-7} $\Omega \cdot$ cm^2, but otherwise identical material parameters. We believe that improvement in the contact quality, combined with a significant increase in the peak current density obtained by optimizing the DBD material parameters, will lead to devices having f_{MAX} near 600 GHz.

This work was supported by the U.S. Army Research Office and by NASA.