large detector received only a constant level, and it was used to cancel the laser amplitude noise.

The sample in this experiment was a Mitsubishi AlGaAs crank transverse junction stripe laser [7]. It was prebiased below threshold (I_b = 20 mA, I_{th} = 22 mA) and a 2-mA, 100-MHz sine wave signal was used to modulate the charge density within the cavity. The optical probe beam was focused onto the top of the AlGaAs laser sample, and x-y scanned across its surface. The measurements show uniform charge density along the edges of the laser cavity, and longitudinal spatial hole burning along the laser cavity center. A spatial rate equation analysis, including carrier diffusion, qualitatively agrees with the experimental results.

The temporal variation of carriers within the laser cavity was also observed by focusing the picosecond 1.3-μm laser probing spot to the center of the device. The AlGaAs laser sample was again biased below threshold and pulsed with a comb generator 10, 15, and 30 mA above threshold. The measurements demonstrate that the internal charge level overshoots and then clamps at the threshold level, where the amount of overshoot is proportional to the overdrive current.

In the future, shorter pulse laser systems will allow us to noninvasively observe picosecond carrier dynamics with micrometer spatial resolution over the entire length of the laser cavity.

[1] W. Both, R. Rimpler, G. Erbert, G. Stadermann, A. Klehr, and U. Zeimer, *IEE Proc. J.*, vol. 134, p. 95, 1987.
[2] H. Kawaguchi and K. Takahei, *IEEE J. Quantum Electron.*, vol. QE-16, p. 706, 1980.
[3] M. P. Kesler and E. P. Ippen, *Appl. Phys. Lett.*, vol. 51, p. 1765, 1987.
[4] H. K. Heinrich, D. M. Bloom, and B. R. Hemenway, *Appl. Phys. Lett.*, vol. 48, p. 1066, 1986.
[5] U. Keller, S. K. Diamond, B. A. Auld, and D. M. Bloom, *Appl. Phys. Lett.*, vol. 53, p. 388, 1987.
[6] T. Wilson, D. K. Hamilton, *Optica Acta*, vol. 31, pp. 453–465, 1984.
[7] K. Isshiki, N. Kaneno, H. Kumabe, H. Namizaki, K. Ikeda, and W. Susaki, *J. Lightwave Tech.*, vol. LT-4, pp. 1475–1481, 1986.

VIA-7 Monolithic Infrared Sensor Array in Heteroepitaxial $Pb_{1-x}Sn_xSe$ on Si with 12-μm Cutoff Wavelength

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An array of photovoltaic infrared sensors with cutoff wavelength as high as 12 μm has been fabricated for the first time in a narrow-gap semiconductor layer ($Pb_{1-x}Sn_xSe$, LTS) grown heteroepitaxially on Si.

LTS on Si heteroepitaxy was achieved using an intermediate stacked ≈2000-Å-thick epitaxial CaF_2-SrF_2-BaF_2 buffer layer to overcome the large lattice mismatch (14 percent) and, even more important, thermal expansion mismatch between lead chalcogenides and Si. The fluoride as well as the ≈3-μm-thick LTS layer are grown by molecular-beam epitaxy (MBE). Photovoltaic IR sensors are formed with blocking Pb contacts and are backside illuminated. We already used the same technique to demonstrated first single LTS sensors with 9.5 cutoff wavelength [1] as well as PbTe-sensor arrays (5.5-μm cutoff) on Si [2]. The sensors have 50 × 100 μm^2 active areas, and an array consists of 66 elements.

The LTS sensors are diffusion noise current limited down to 95 K, followed by a depletion noise dominated region. Resistance-area products are up to 0.3 Ω · cm^2 at 77 K (cutoff 11.6 μm), and quantum efficiencies are >0.25 without antireflection coating. This corresponds to a junction noise limited detectivity $D^* > 2 \times 10^{10}$ cm Hz/W.

Despite our sensors are still far from being optimized, the sensitivities achieved (as deduced from the R_0A values) are only ≈5 times lower than those of state-of-the-art photovoltaic $Hg_{1-x}Cd_xTe$ (CMT) sensors with the same cutoff wavelength. Such CMT sensors are fabricated in bulk CMT or in epitaxial layers on CdTe or CdZnTe (but not on Si!) substrates.

The mean R_0A value for a whole array measured at 87 K is 0.05 Ω · cm^2. All sensors are properly working and withstand multiple temperature cycling. The spread in cutoff wavelengths is below 0.2 μm within the array. Due to the positive temperature dependence of the bandgap energy, the cutoff wavelengths increase with decreasing temperatures, they reach 12 μm at about 60 K.

We also present first results which demonstrate that LTS growth and IR sensor fabrication is compatible to be applied with active silicon substrates, thus allowing the construction of a heteroepitaxial but fully monolithic narrow-gap semiconductor on silicon IR focal plane array. In addition, LTS can be grown on large wafers since MBE growth of LTS does not pose special problems, and the material homogeneity required for an acceptable spread in cutoff wavelengths is much less stringent for LTS compared to CMT.

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[1] H. Zogg and P. Norton, in *IEDM Tech. Dig.*, 1985, p. 121.
[2] C. Maissen, J. Masek, H. Zogg, and S. Blunier, *Appl. Phys. Lett.*, vol. 53, p. 1608, 1988.

VIA-8 GaAs Photodetectors Integrated With Lithium Niobate Waveguides

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The material of choice for guided wave electrooptic devices has been $LiNbO_3$, rather than semiconductors, because of its larger electrooptic coefficients, lower coupling loss to fibers, lower propagation loss, and the ease of device fabrication. Nevertheless, there has been a steady shift in interest away from $LiNbO_3$ toward semiconductors because of the possible integration of electrooptic devices with photodetectors, transistors, and lasers. In spite of the obvious benefits, integration of semiconductor and $LiNbO_3$ devices has not been seriously considered before because of the disparity between the two materials. We report here on the application of epitaxial liftoff [1] to achieve the first integration of a semiconductor device with a $LiNbO_3$ optical waveguide and on the optical interaction between the two. The semiconductor device is a GaAs metal-semiconductor-metal photodetector [2] that was processed entirely after the epitaxial liftoff. Because of the high index of refraction difference between the two materials, light evanescently couples readily from the low-index waveguide into the high-index GaAs photodetector.

The detector material was grown by molecular-beam epitaxy on GaAs and consisted of 250 nm of undoped GaAs above a 50-nm sacrificial AlAs layer. The GaAs epilayer was lifted off from the GaAs substrate using HF, which selectively etches the AlAs layer, and the 3 mm × 7 mm epilayer film was placed directly on a $LiNbO_3$ substrate where it is held by van der Waal forces. The $LiNbO_3$ had a planar waveguide formed by proton exchange before the epilayer transfer. After the transfer, we formed an array of MSM detectors on the GaAs by patterning Schottky metal. The array completely covered the GaAs and consisted of 100-μm-wide metal lines separated by 5-μm gaps. The metal lines extended completely across the GaAs film and ran perpendicular to the direction of light propagation so that the active region of each photodetector absorbs light for about 5 μm. We did not attempt to optimize the electrical and optical parameters as the main purpose of this work was to establish optical interaction between the waveguide and photodetector.

HeNe laser light (λ = 633 nm) was prism coupled into the waveguide. Light was totally extinguished within ~1 mm from the edge of the GaAs film. The photocurrent of the first detector, which was about 150 μm behind the leading edge of the GaAs, was 6 μA with 0.5-mW incident laser power. The second detector, 100 μm behind the first, gave 4 μA of photocurrent. These photocurrents correspond to a waveguide-detector absorption coefficient of 40 cm^{-1}, in agreement with estimates based on the effective index approximation.

We have demonstrated the feasibility of integrating a semiconductor photodetector with $LiNbO_3$ waveguides. All fabrication steps for the photodetectors are done after the epitaxial liftoff allowing the photodetector size and placement to be matched to the waveguides with photolithographic accuracy. Light couples from the $LiNbO_3$ waveguide to the GaAs photodetector indicating the two are in good optical contact with little or no intervening low index material such as air. It is expected that, with the present technique of integrating and optically coupling semiconductor and $LiNbO_3$ devices, high-performance optoelectronic integrated circuits that take advantage of the strengths of each material will be possible.

[1] E. Yablonovitch, T. Gmitter, J. P. Harbison, and R. Bhat, *Appl. Phys. Lett.*, vol. 52, p. 2222, 1987.
[2] T. Sugeta, T. Urisu, S. Sakata, and Y. Mizushima, *Japan J. Appl. Phys.*, vol. 19, suppl. 19-1, p. 459, 1980.

VIA-9 Room-Temperature Continuous Wave Vertical Surface-Emitting GaAs Injection Lasers Grown by Molecular-Beam Epitaxy—K. Tai, R. J. Fischer, C. W. Seabury, N. A. Olsson, D. T. C. Huo, Y. Ota, D. G. Deppe, A. Y. Cho, AT&T Bell Laboratories, Murray Hill, NJ 07974.

Room-temperature continuous-wave oscillation with emission power in excess of 1 mW was achieved in vertical-cavity surface-emitting lasers containing a 0.5-μm-thick GaAs active layer sandwiched between a distributed Bragg reflector (DBR) and a metal-DBr hybrid reflector grown by MBE. The threshold current is 40 mA for a 15-μm-diameter device. The temperature dependence of the threshold current gives $T_0 = 115$ K.

VIB-1 InGaAs Superconducting JFET's with Nb Electrodes—A. W. Kleinsasser, T. N. Jackson, D. McInturff, G. D. Pettit, F. Rammo, and J. M. Woodall, IBM Research Division, T. J. Watson Research Center, Yorktown Heights, NY 10598.

A field-effect transistor can exhibit superconducting properties if the source and drain contacts are superconductors [1]. It is only recently that such effects have been observed experimentally, and the most significant result published to date is the report of 0.1-μm Si MOSFET's with Nb electrodes [2]. We have fabricated InGaAs junction FET's having Nb source and drain electrodes with submicrometer spacings. The devices exhibit gate-controlled supercurrents as large as 8 mA/mm at 4.2 K. This value of controlled supercurrent is larger than any previously reported for superconducting field-effect devices. The channel material was n-type $In_{0.53}Ga_{0.47}As$, epitaxially grown by MBE on InP substrates. Gate control was achieved using a p-n junction which was buried below the channel. This structure allowed the Nb superconductor to be deposited directly onto the freshly grown channel layer to insure a clean superconductor–semiconductor contact, which is essential for obtaining optimum superconducting properties. The superconducting electrodes were patterned by RIE.

From the materials systems for which viable FET technologies exist, InGaAs was chosen because it offers two significant advantages: 1) A low ($\simeq 0.2$ eV) Schottky-barrier height at the source and drain contacts and small carrier mass result in a large tunneling probability, allowing a strong proximity effect coupling of superconducting properties into the channel region. 2) A large mobility and small effective mass result in a large coherence length in the channel. This allows relatively long source-drain separations for a given supercurrent density, which enabled us to achieve record levels of controlled supercurrent in structures defined by optical lithography. The use of InGaAs lattice-matched to InP allowed us to fabricate p-n junctions in the InGaAs layers with excellent properties. This is important in avoiding junction leakage, which would otherwise complicate the device measurements due to nonequilibrium effects. Experimental device results and comparison with theory will be presented.

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[1] For a recent discussion, see A. W. Kleinsasser and T. N. Jackson, *Proc. 1988 Appl. Supercond. Conf.*, to be published in *IEEE Trans. Magnetics*, 1989.
[2] T. Nishino, M. Hatano, H. Hasegawa, F. Murai, T. Kure, A. Hirawa, K. Yagi, and U. Kawabe, *IEEE Electron Device Lett.*, vol. 10, p. 61, 1989.

VIB-2 A Single-Chip SQUID Having an Improved Superconducting Storage Loop—N. Fujimaki, H. Tamura, H. Suzuki, T. Imamura, S. Hasuo, and A. Shibatomi, Fujitsu Laboratories, Ltd., 10-1, Morinosato-Wakamiya, Atsugi 243-01, Japan.

We have integrated both a SQUID sensor and a superconducting feedback circuit on a single chip [1]. Such an integration is useful for constructing multichannel SQUID system because it eliminates the need for the massive feedback circuit outside the chip and many electrical cables connected them to the SQUID sensors.

In this report, we improved the dynamic range of the single-chip SQUID by more than two orders of magnitude and obtained high sensitivity.

In the single-chip SQUID, the sensor is ac biased and produces a pulse sequence. The superconducting feedback circuit consists of a superconducting loop and a write gate, a two-junction interferometer. The gate adds a flux quantum to the loop when it receives a pulse from the sensor. The stored flux is fed back to the sensor through magnetical coupling. This feedback maintains the sum of the input flux and the feedback flux at zero, and we can know the input flux by measuring the feedback flux. Thus, the dynamic range of this SQUID is limited by the capacity of storing flux quanta in the loop.

In the new design, we increased the loop inductance from the previous 20 nH to 30 μH. The estimated capacity becomes $\pm 1.5 \times 10^5$. As it is necessary to decrease the stray coupling between the loop and the pickup coil or the other SQUID chip, we divided the loop into 32 spiral coils, and wound each coil inversely to cancel each magnetic flux at the distance. The feedback coupling is designed so that one flux quantum, Φ_0, in the loop is coupled to the sensor as $5.6 \times 10^{-5}\ \Phi_0$ that is nearly the same as the thermal noise of the sensor, $(S_\phi \Delta f)^{1/2}$, where S_ϕ is the flux spectral density and Δf is the frequency bandwidth.

The chip was fabricated using $Nb/AlO_x/Nb$ junction technology, Mo resistor, and SiO_2 insulation [2]. The minimum line width is 2.5 μm and the chip size is 9.4 mm $\times$ 5 mm. We operated the chip. When a large input was applied, the loop stored flux quanta up to $\pm 2 \times 10^4$. This number is more than two orders of magnitude larger than the previous value, $\pm 10^2$; however, it is reduced from the design value, $\pm 1.5 \times 10^5$. This reduction is due to the circulating current in the loop caused by the flux trappings. So, we consider that the dynamic range can be further improved by protecting the loop from the flux trapping or at least by releasing the circulating current. The sensitivity was $10^{-6}\ \phi_0/\mathrm{Hz}^{1/2}$ that is nearly the same level of the conventional dc SQUID. These results, wide dynamic range and high sensitivity, show that the single-chip SQUID is available as a key element for constructing multichannel SQUID system in biomagnetic application.

[1] N. Fujimaki, H. Tamura, T. Imamura, and S. Hasuo, *IEEE Trans. Electron Devices*, vol. 35, p. 2412, 1988.