

Chapter 3. High-Frequency (>100 GHz) Electronic Devices

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3.1 Millimeter Wave and Infrared Superconducting Focal-plane Receiver Arrays

Sponsor

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Project Staff

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Millimeter wave and far-infrared frequencies remain one of the most underdeveloped frequency ranges, even though the potential applications in remote sensing and communication are significant. This is because the millimeter wave and far-infrared frequency range falls between two other frequency ranges in which conventional semiconductor devices are usually operated. One is the microwave frequency range, and the other is the near-infrared and optical frequency range. Semiconductor devices which utilize the classical diffusive transport of electrons, such as diodes and transistors, have a high frequency limit. This limit is set by the time it takes for electrons to travel a certain distance. Currently, electron mobility and the smallest feature size which can be fabricated by lithography limit the frequency range to below 100 GHz. It is not very likely that this limit can be pushed much higher. Semiconductor devices based on quantum mechanical interband transitions, however, are limited to frequencies higher than those corresponding to the semiconductor

energy gap, which is higher than 10 THz for most bulk semiconductors. Therefore, a large gap exists from 100 GHz to 10 THz in which very few devices are available.

The gap energies of conventional superconductors, such as Nb, are in the range of 100 GHz to 2 THz. This coincidence makes superconducting devices natural candidates for millimeter and submillimeter wave applications. At millimeter wave frequencies, the superconducting video detectors have been demonstrated to have quantum efficiency $e/\hbar\omega$, that is, a transport of one electron for one incoming photon; while the superconducting coherent receivers have been demonstrated to have their sensitivities limited only by the zero-point fluctuation of vacuum. Such receivers have been used widely in astrophysical studies. More applications are feasible in space-based communication and far-infrared spectroscopy which requires ultimate sensitivity.

We are currently developing a novel quasioptical scheme to couple the millimeter-wave and infrared signals to the superconducting devices through a combination of an etched horn antenna and a planar antenna supported by a thin ($\sim 1 \mu\text{m}$) membrane, as shown in figure 1. This scheme combines the advantages of easy fabrication of lithographic thin-film structures and high antenna efficiencies of horn antennas. Because of the absence of substrate losses in this scheme, it is expected that a THz receiver can be constructed using all-Nb superconductor-insulator-superconductor (SIS) junctions. More important, because of the cumbersome mechanical structures used in conventional waveguide technology, microwave receivers have been single-element devices, as opposed to CCD imaging arrays at optical frequencies. Spatial scan has been

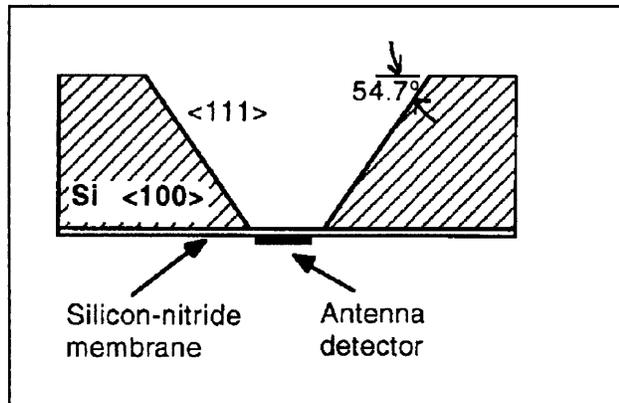


Figure 1. Example of anisotropic etching in a $\langle 100 \rangle$ silicon wafer. The opening of the wafer yields a pyramidal horn with a flare angle of 35.5° .

achieved mechanically. Using the novel quasi-optical scheme mentioned above, focal-plane detector arrays can be easily fabricated lithographically on a single Si wafer, as shown in figure 2, and far-infrared imaging becomes highly feasible.

3.2 Photon-assisted Quantum Transport in Quantum Point Contacts

Sponsor

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Project Staff

Professor Qing Hu, Rolf A. Wyss in collaboration with Christopher C. Eugster and Professor Jesús A. del Alamo

Quantum transport has been one of the most active fields in solid-state physics in recent years. Advances in material preparation have made quantum phenomena profound in electron transport for many semiconductor quantum devices such as quantum point contacts, quantum dots, quantum wires, quantum wells, superlattices, etc. In clean samples and at low temperatures, electrons can travel through the whole sample without suffering phase-destructive scattering. Extensive work has been done to study various features of such phase-coherent quantum transport. However, the experiments reported so far are limited to dc transport measurements or far-infrared spectroscopy measurements.

It is well known in the field of superconducting tunneling that photons can assist the tunneling process, provided the tunneling is elastic so that electrons do not suffer inelastic scattering. In a

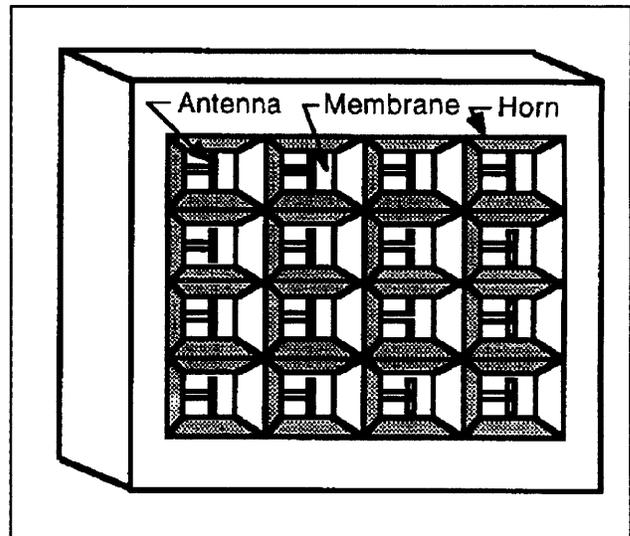


Figure 2. Perspective view of a two-dimensional horn imaging array.

broad sense, elastic tunneling is a phase-coherent quantum transport in a classically forbidden region. Therefore, all the results of photon-assisted tunneling can be applied to the study of photon-assisted quantum transport in semiconductor devices. The study of the photon-assisted quantum transport can substantially improve our understanding of quantum transport phenomena. Novel long-wavelength optoelectronic devices may also emerge from this research.

In this NSF-sponsored project, we are studying the interaction between far-infrared photons and ballistic electrons in a quantum point contact (see schematic shown in figure 3(a)). The ballistic transport of electrons through the quantum point contact can be analyzed using an electron waveguide (see cross section shown in figure 3(b)). The width d of the waveguide can be varied by the gate voltage. Thus, the number of waveguide modes (subbands below the Fermi energy) which contribute to the source/drain conduction can be modulated by the gate voltage. Because electrons are fermions which obey Pauli's exclusion principle, each waveguide mode contributes exactly $2e^2/h$ to the source/drain conductance. At certain negative gate voltages, such as shown in figure 3(b), the Fermi energy is suppressed below the first subband. Under this bias condition, the electron waveguide is pinched off, and the source/drain conductance is zero in the absence of radiation.

However, in the presence of radiation with appropriate polarity and photon energy, a source/drain current can be induced when the gate voltage is below the pinch off. The coupling of coherent radiation at ~ 300 GHz to the quantum point contact of submicron size is via a planar antenna

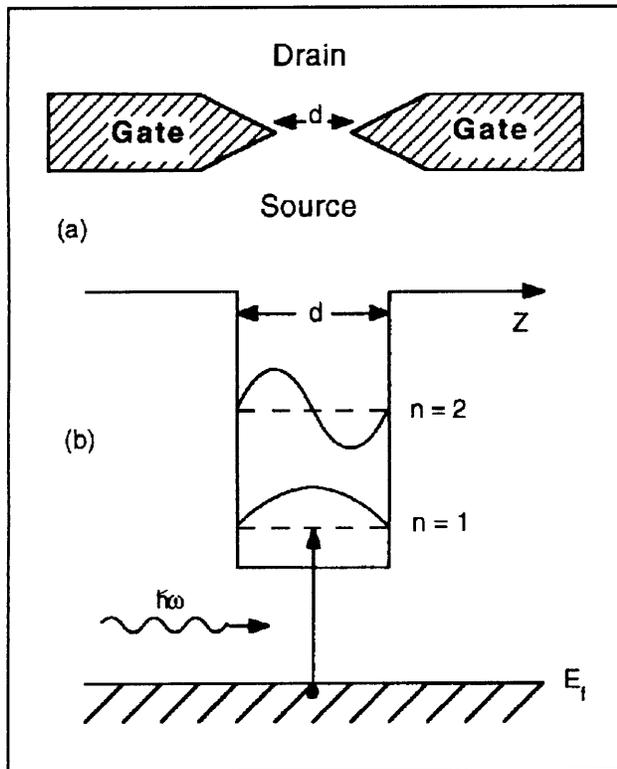


Figure 3. (a) Schematic of a quantum point contact. (b) Schematic of an electron waveguide which can be used to analyze the transport of electrons through the quantum point contact shown in (a).

with terminals that also serve as the split-gate of the quantum point contact, as shown in figure 4. In this scheme, the electrical field of the radiation is polarized perpendicular to the source/drain conduction path. Thus, intersubband transition can be excited by the far-infrared photons. At a gate voltage slightly below the pinch off (~ 1 mV), we have observed a photon-induced source/drain current with an amplitude comparable to that corresponding to the first quantized conductance step. We are currently optimizing the coupling efficiency of our system and carrying out a systematic study of photon-induced source/drain current as functions of the frequency and power of far-infrared radiation.

3.3 High- T_c Superconducting Josephson Devices

Sponsor

Defense Advanced Research Projects Agency
Contract MDA 972-90-C-0021

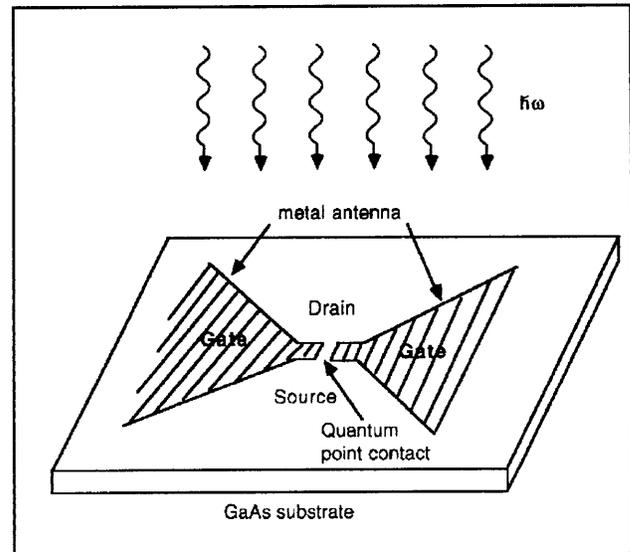


Figure 4. Schematic of an antenna-coupled quantum point contact (or electron waveguide). The incident radiation is usually focused by a lens onto the planar antenna, which in turn focuses the photon field into the small gap region between the two antenna terminals.

Project Staff

Professor Qing Hu, Rajesh K. Gupta, Scott R. Velazquez in collaboration with Twente University, The Netherlands

Many superconducting analog devices have been demonstrated to have higher sensitivities, higher speed and frequency limit, and lower power dissipation than competing semiconductor devices. Among them, the most successful ones are SQUIDs (Superconducting QUantum Interference Devices) and millimeter-wave detectors.

The discovery of superconductors with the superconducting transition temperature higher than liquid nitrogen temperature (high- T_c superconductors) has opened up new and exciting possibilities in electronic device technology. High temperature version of the superconducting devices mentioned above will find a much wider-range application wherever refrigeration is a problem. The key element of all superconducting analog and digital devices is the Josephson junction. This junction is formed by two superconductors weakly coupled together electrically. The supercurrent flowing through the Josephson junction oscillates at the Josephson frequency $f = 2eV/h$ (500 GHz/mV), when a voltage is applied across the junction. Most of the useful applications of Josephson devices result from this high-frequency oscillation, such as high-frequency and high-speed signal processors and high-sensitivity SQUID magnetometers whose high precision results from averaging over many cycles of the Josephson oscillations.

In collaboration with the Dutch group headed by Professor Horst Rogalla, which is the leading group in fabricating high-Tc Josephson junctions with the most desirable properties, we are studying the response of high-Tc Josephson junctions to radiations at 100 GHz and above. We are also studying the effect of random noise, such as thermal and shot noise, on the performance of high-Tc Josephson devices. The immediate results of this research will be the development of liquid nitrogen cooled millimeter-wave and infrared detectors. Such devices will be very useful in extensive space-based sky and earth surveys, such as the one in the NASA's project "Mission to the Planet Earth," in which the detectors can be passively cooled by radiative cooling and in far-infrared spectroscopy. The study of the high-frequency response and noise effect will benefit all the future development of superconducting signal processors using high-Tc Josephson junctions.

3.4 Far-infrared (THz) Lasers Using Multiple Quantum Wells

Project Staff

Professor Qing Hu, Jurgen H. Smet, Edouard A. Garcia in collaboration with Professor Clifton G. Fonstad

Semiconductor quantum wells are man-made quantum mechanical systems in which energy levels can be chosen by changing the sizes of the quantum wells. Typically, the frequency corresponding to the intersubband transitions is in the far-infrared or THz range. Naturally, long-wavelength photoelectric devices, such as far-infrared lasers, which utilize the intersubband transitions, have been proposed and subsequently studied. Significant progress has been made recently toward this goal. Large oscillator strengths of intersubband transitions have been observed in far-infrared absorption spectroscopy experiments. An intersubband spontaneous emission with a power level of $\sim 10^{-7}$ W has been observed. Although these preliminary results are encouraging, two major challenges to building a quantum-well far-infrared laser remain. One is to achieve a high degree of population inversion

between two subband levels, and the other is the confinement of photons within the active region. Optical pumping suffers from low efficiency and low modulation speed, thus it will be difficult to achieve a sufficient gain to maintain a lasing oscillation, so that optical pumping will be unsuitable for communication applications. As far as optical confinement is concerned, the usual dielectric waveguide confinement method, commonly used in optical and near-infrared laser systems, is not applicable at far-infrared frequencies because the confinement (on the order of a wavelength) is too large compared to the dimensions of the active region.

In this project, we will use a novel MQW (multiple quantum-well) device to circumvent these two problems. In this device, with an energy band diagram that is shown in figure 1 with and without a dc bias voltage, electrons are injected selectively into an upper subband level of a wide lasing quantum well through a narrow filter quantum well. After relaxing into a lower subband in the lasing well, the electrons are then removed selectively to a collector through another narrow filter quantum well. This filter well prevents the electrons in the upper subband level from tunneling out to the collector. Using this method of selective injection and removal, a high degree of population inversion can be achieved if the tunneling rate of the electrons from the ground state to the collector is greater than the relaxation rate of the electrons from the upper subband to the ground state. Our calculation indicates that this should easily be achieved.

In the proposed MQW laser device, a parallel-plate waveguide that confines the photons can be formed between a heavily doped semiconductor injector and collector. At a doping level of $2 \times 10^{18}/\text{cm}^3$, we can raise the plasma frequency in the injector and collector to about 17 THz. It has been reported that the electron mobility, m , for such a high doping level is $5 \times 10^3 \text{ cm}^2/\text{Vs}$. This plasma is mostly reflective with a penetration depth as short as $0.8 \mu\text{m}$ for a lasing frequency in the range of 1-8 THz. This confinement is sufficiently tight so that the lasing threshold current density is on the order of several hundred A/cm^2 , which should be achievable.

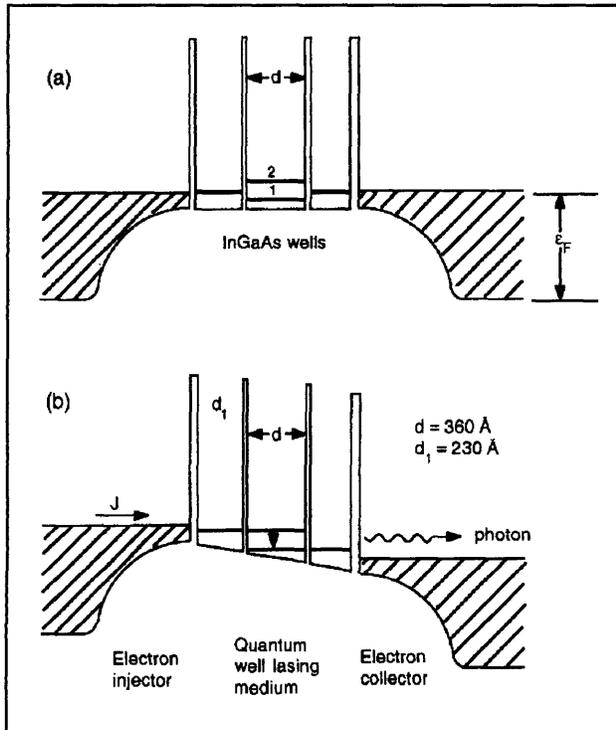


Figure 5. Band profiles (not drawn in proportion) of the proposed far-infrared laser device under (a) zero-bias, and (b) lasing condition in which $V_{\text{bias}} \sim (E_2 - E_1)/e \approx 20$ mV. The device consists of one narrow quantum-well energy filter on both sides of the lasing quantum well. The width of the narrow filter wells (made of $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$) is approximately 230 \AA so the energy of its first subband lies in between the first two subbands in the wide lasing well whose width is approximately 360 \AA , which will have a radiation frequency of 5 THz due to the intersubband transitions.

3.5 Research Facility

We have cryogenic systems which can cool devices down to 1.5 K. Each experimental set-up is equipped with low-noise electronic data acquisition systems which are capable of measuring current signals at subnonamp levels and voltage signals at submicrovolt levels. We also have

microwave sweeper and spectrum analyzer up to 20 GHz. The most unique pieces of equipment in Professor Hu's group are various millimeter-wave and infrared sources which can generate coherent and incoherent radiation up to 30 THz. These include: Gunn oscillators at W-band frequencies (75-110 GHz); a frequency doubler, tripler, and quadrupler using Schottky diodes at 200, 300, and 400 GHz; an optically pumped far-infrared laser which generates coherent radiation up to 8 THz; and an infrared Fourier transform spectrometer which is capable in performing linear spectroscopy from 45 GHz to 30 THz and beyond.

3.6 Publications

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