

Miniaturization: enabling technology for the new millenium

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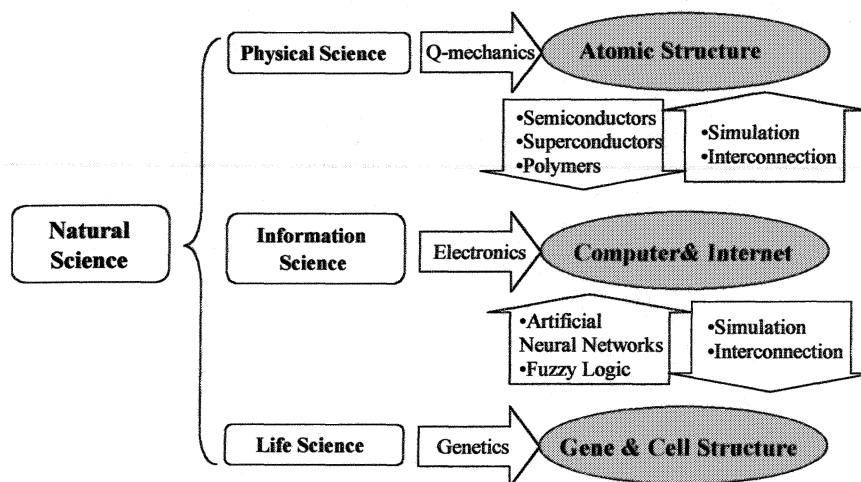
ABSTRACT

The history of semiconductor devices has been characterized by a constant drive towards lower dimensions in order to increase integration density, system functionality and performance. However, this is still far from being comparable with the performance of natural systems such as human brain. The challenges facing semiconductor technologies in the millenium will be to move towards miniaturization.

The influence of this trend on the quntum sensing of infrared radiation is one example that is elaborated here. A new generation of infrared detectors has been developed by growing layers of different semiconductors with nanometer thicknesses. The resulted badgap engineered semiconductor has superior performance compared to the bulk material. To enhance this technology further, we plan to move from quantum wells to quantum wire and quantum dots.

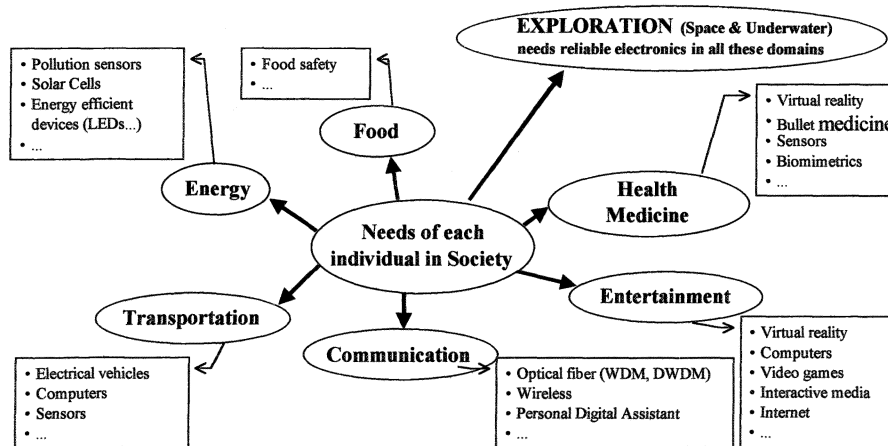
1.INTRODUCTION

The 20th century has witnessed the phenomenal rise of Natural Science and Technology into all aspects of human life. Three major sciences have emerged and marked this century: Physical Science which has strived to understand the structure of atoms through quantum mechanics, Life Science which has attempted to understand the structure of cells and the mechanisms of life through biology and genetics, and Information Science which has symbiotically developed the communicative and computational means to advance Natural Science.



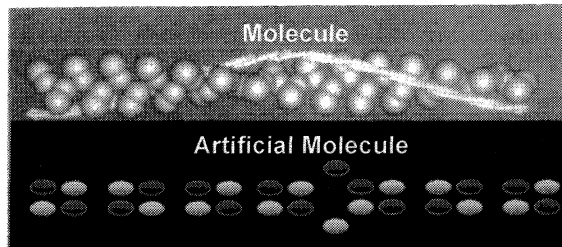
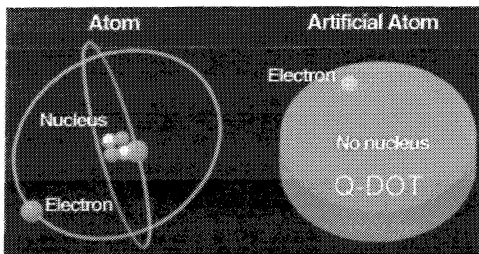
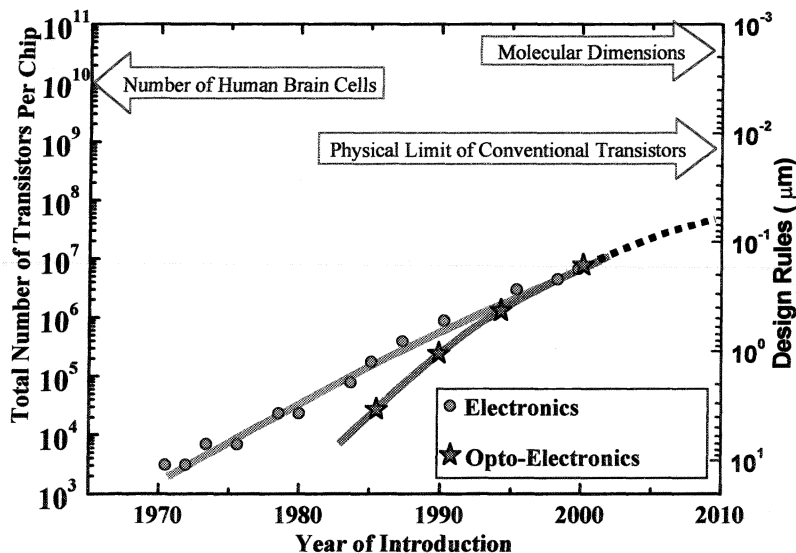
Microelectronics has become one of today's principle enabling technologies supporting these three major sciences and touches every aspect of human life: food, energy, transportation, communication, entertainment, health/medicine and exploration. For example, microelectronic devices have now become building blocks of systems which are used to monitor food safety and pollution, produce electricity (solar cells) or use energy more efficiently (LED), control electrical vehicles (automobiles), transmit information (optical fiber and wireless communications), entertain (virtual reality, video games, computers), help cure or enhance the human body (artificial senses, optically activated medicine) and support the exploration of new realms (space, underwater).

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Although impressive progress has been achieved, microelectronics is still far from being able to imitate Nature in terms of integration density, functionality and performance. For example, a state-of-the-art low power Pentium II processor consumes nearly twice as much power as a human brain, while it has 1000 times fewer transistors than the number of cells in a human brain. Forecasts show that the current microelectronics technology is not expected to reach similar levels because of its physical limitations.

A different approach has thus been envisioned for future advances in semiconductor science and technology in the 21st century. This will consist of reaching closer to the structure of atoms, by employing *nanoscale electronics*. Indeed, the history of microelectronics has been, itself, characterized by a constant drive to imitate natural objects (e.g. the brain cell) and thus move towards lower dimensions in order to increase integration density, system functionality and performance (e.g. speed and power consumption).



Thanks to nanoelectronics, it will not be unforeseeable in the near future to *create* artificial atoms, molecules, and integrated multifunctional nanoscale systems. For example, as illustrated above, the structure of an atom can be likened to that of a “quantum dot” where the three-dimensional potential well of the quantum dot replaces the nucleus of an atom. An artificial molecule can then be made from a chain of artificial atoms. In the following part, the influence of this miniaturization approach on a new generation of infrared detectors at Center for Quantum Devices (CQD) is presented.

2. TYPE-II SLs FOR UNCOOLED IR DETECTION

Uncooled infrared (IR) detectors are required for low-cost, lightweight sensor systems that have both military and commercial applications. Commercially available uncooled IR sensors use ferroelectric or microbolometer detectors. These sensors are inherently slow and cannot detect rapid signal changes needed for many applications. Some of the applications which require a fast detector response time ($\tau < 30$ msec) are: free-space communication, proximity fuzes, active infrared countermeasure systems, non-invasive medical monitoring, and LIDARs. Although photon detectors have frequency responses in the megahertz range, their high temperature detectivity is severely degraded due to physical limitations. The existing infrared photon detectors can be categorized as interband, which are mostly HgCdTe and InAsSb, or intersubband quantum well infrared detectors (QWIP)¹. Unfortunately, fast Auger recombination rate in the interband detectors² and high thermal generation rate in the intersubband detectors decrease their performance for room temperature operation drastically.

As another alternative for infrared photodetectors, type-II superlattices have been studied which were originally suggested by Sai-Halasz and L. Esaki³. In order to realize Auger suppression at room temperature, we have developed a new type-II superlattice detector design⁴. The experimental results show nearly one order of magnitude lower Auger recombination rate at room temperature in such detectors compared to typical intrinsic (HgCdTe) detectors with similar bandgap. Single-element detectors⁵ shows a detectivity of $1.3 \times 10^8 \text{ cmHz}^{1/2}/\text{W}$ at $11 \mu\text{m}$ at room temperature which is comparable to microbolometers under similar conditions. However, the measured response time of the detector is less than 68 nsec which is more than six orders of magnitude faster than microbolometers.

2.1 THEORY AND MODELING

For the simulation of energy bands and the electrons and holes wavefunctions in the superlattices, we used an 8-band $\mathbf{k}\cdot\mathbf{p}$ approach. Finite Element Method (FEM) was used to generate the system of differential equations. The band structure of type-II superlattices was engineered for lower Auger recombination rate, since Auger is the primary recombination mechanism at high temperatures in narrow gap IR detectors and lasers. Figure 1 shows the result of such simulation for the band structure of two superlattice structures in the k -space. Numerical calculation shows that the Auger resonance between the conduction, heavy-hole, and light-hole bands (Auger 7) is much less in the left structure since the light-hole band is out of the resonance for low values of $k_{\perp}$.

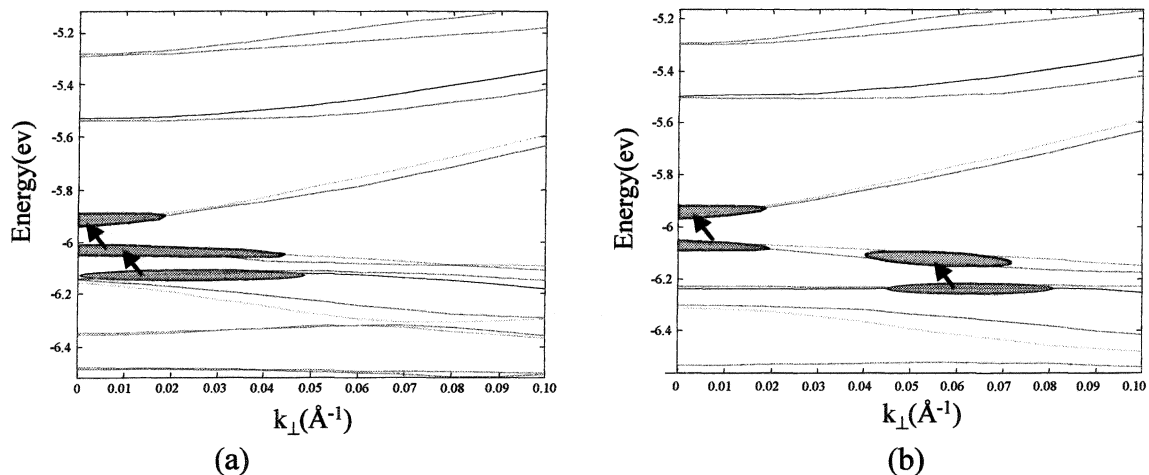


Fig.1. (a) Energy band structure of InAs/InSb/GaSb/InSb 48Å/3Å/48Å/3Å and (b) InAs/InSb/GaSb/InSb 48Å/3Å/30Å/3Å superlattices calculated with the eight-band $\mathbf{k}\cdot\mathbf{p}$ simulation.

2.2. GROWTH AND CHARACTERIZATION

The optimized structures were grown in a Varian Modular Gen-II solid source molecular beam epitaxy (MBE) system. The reactor is designed to grow Sb-based material with high uniformity on 3 inch wafers. The growth temperature, III/V flux ratio, and the growth rate of the material were optimized for minimum compositional and thickness variation over large areas⁶. Theoretical calculation shows that as the cut-off wavelength of the superlattice increases, its sensitivity to the composition and to the thickness superlattices increases. On the other hand, it has been shown that the interface layer in type-II superlattices can considerably affect the optical and electrical properties of this material system. In order to control the interface accurately, migration-enhanced epitaxy was used to control the intermixing at the interfaces. Our experimental results show that atomically flat surfaces over large areas can be grown at low temperatures with this technique. The low growth temperature will also ensure low diffusion of arsenic atoms through the interfaces which leads to lower background carrier concentration.

In order to fulfill the tight material quality requirement (composition and interface control), epitaxial layers were systematically characterized using a combination of structural, optical, and electrical techniques. For structural characterization, high resolution five-crystal x-ray diffraction system, scanning electron microscopy (SEM), and atomic force microscopy (AFM) were used. The average lattice constant and the period of the superlattices were accurately measured with a high-resolution x-ray diffraction system. The cross section of the samples was studied with SEM. The surface roughness of the samples was measured with AFM system, since SEM cannot provide comparable resolution and contrast. For optical characterization we used photoluminescence (PL), and Fourier Transform Infrared (FTIR) techniques in the 77K and 300K range. PL measurement provided information about the material quality, and in particular on the generation-recombination mechanism. FTIR system was used for absorption coefficient measurements. This information were used to estimate the internal quantum efficiency and the effective bandgap of the superlattices. For electrical inspection we used Hall measurement system, parameter and spectrum analyzers. Magnetic-dependent Hall measurement of the superlattices provided some information about the electron and hole concentration as well as their mobilities. The minority carrier lifetime was extracted from the measured quantum efficiency, carrier mobility, carrier concentration, and optical responsivity of the photoconductors.

2.3. DEVICE PROCESSING AND MEASUREMENT

Photoconductor devices were fabricated by standard lithography and subsequent etching with $\text{H}_3\text{PO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$ (1:1:10) solution. For ohmic contacts, Ti/Au (500 Å /2000 Å) was deposited and then the contacts were defined by lift-off technique. No anti-reflection coating or surface passivation was employed.

Spectral photoresponse of the device was measured using a Galaxy 3000 FTIR spectrometer system. The samples were illuminated through the front side at normal incidence. The absolute response of the photodetectors was calculated using a blackbody test set, which is composed of a blackbody source (Mikron 305), preamplifier (EG&G PA-100), lock-in amplifier (EG&G 5209), and chopper system (Stanford Research System SR540). Figure 2 (a) shows the spectral response of the device in the 2-17 μm wavelength range at 78K and 300K. To assess the temperature dependence, the current responsivity of the device was measured at 10.6 μm wavelength from 78K to room temperature at constant electrical field.

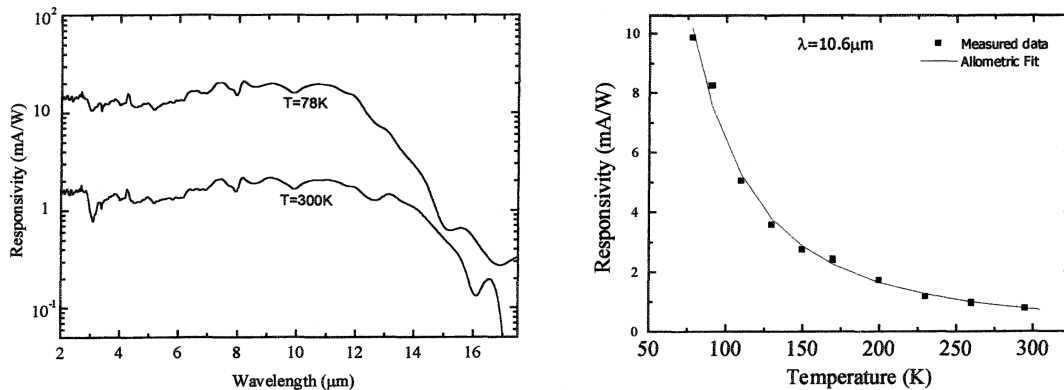


Fig.2. (a) The responsivity spectra of the device at 78K and 300K with an in-plane electrical field of 5V/cm and (b) current responsivity of the device versus temperature at $\lambda=10.6\mu\text{m}$.

Figure 2 (b) shows the responsivity of the detector at $10.6\ \mu\text{m}$ versus the detector temperature. An Allometric fitting with a general form of $A \cdot T^B$ where T is the temperature and A and B are the fitting variables, shows that the responsivity of the detector is nearly proportional to T^{-2} . This is an unusual behavior since responsivity of the narrow gap material is usually an exponential function of temperature at higher temperatures where Auger recombination is the dominant recombination mechanism.

Also, a field-depended Hall measurement was used to extract the mobility and concentration of electrons and holes in the superlattice at different temperatures. The carriers lifetime was extracted from the optical responsivity of the detectors and the carrier concentrations and mobilities. The extracted carrier lifetime is about 27nsec which is about one order of magnitude longer than the best bulk semiconductors with similar bandgap (HgCdTe) at room temperature. The results of this study shows that the Auger recombination is suppressed⁷ in this material system. Based on the responsivity and noise measurements, the detectivity of the device was calculated as $1.3 \times 10^8\ \text{cm} \cdot \text{Hz}^{1/2} / \text{W}$ at $11\ \mu\text{m}$ at room temperature. This value is several times higher than the detectivity of commercially available high-speed HgCdTe detectors.

In order to study the speed of the detector, the time response of the detector to the infrared pulses generated by a quantum cascade laser was measured. The schematic diagram of the setup is shown in figure 3 (a). The pulse generator and laser driver were inside an Avtech AVR-4A-PW which is capable of generating high power electrical pulses with fall time of about 5 nsec. The quantum cascade laser was uncooled and operated at $\lambda = 8.5\ \mu\text{m}$ with a negligible time delay. An EG&G PA-100 low-noise pre-amp was used to amplify the detector signal. Unfortunately, the pre-amp is not very fast and has a fall time of more than 40 nsec. The output signal of the pre-amp was measured with a Tektronix TDS 520B digital oscilloscope. It shows a fall time of about 68 nsec, as shown in figure 3(b), for the whole setup and hence the detector has a fall time of less than this value.

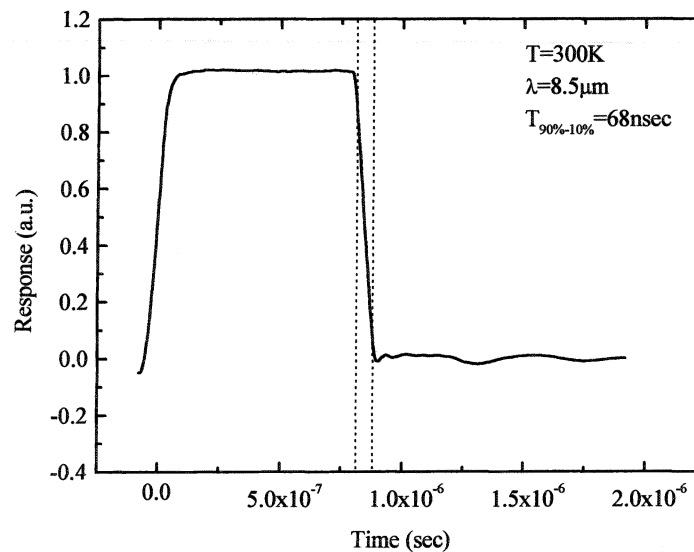
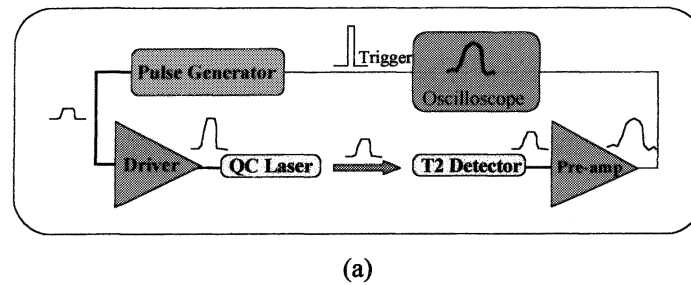


Fig. 3. (a) The schematic diagram of the time response measurement setup. (b) The overall time response of the setup.

3. TYPE-II SUPERLATTICES FOR VLWIR DETECTION

Very long wavelength infrared detectors have many applications such as space based astronomy and pollution monitoring. In this wavelength range, the existing detectors with acceptable uniformity and quantum efficiency are extrinsic silicon detectors which operate below 10K. Consequently, multi-stage cryocoolers are required which are heavy, bulky, and have a short lifetime. These drawbacks are especially important for space based applications, and therefore a detector with higher operating temperature is in great demand.

Recently, we demonstrated the first type-II photoconductive devices grown on GaAs substrate in the $\lambda_c=12\text{ }\mu\text{m}$ to $\lambda_c=22\text{ }\mu\text{m}$ range operating at 80K⁸. Unlike HgCdTe, these detectors showed an excellent energy gap uniformity over a three-inch wafer area which is important for imaging applications. Also, we developed high performance p-i-n photodiodes based on the type-II superlattices. Using bandgap engineering, the energy gap of these devices, consisted of binary InAs/GaSb digital alloy, was designed for the cutoff wavelengths in the $\lambda_c=16\text{ }\mu\text{m}$ to $\lambda_c=25\text{ }\mu\text{m}$ range. In contrast to ternary alloys, the optical response of these devices showed very sharp cutoff edges which indicate excellent energygap uniformity⁹.

Also, experimental results at low temperatures showed good agreement with our theoretical calculation. Figure 4 shows the spectral response of a photodiode at $T=9.5\text{K}$, as well as the theoretically calculated critical energies (shown by arrows). The photoresponse correlates clearly with the transition energies calculated from our four-band model.

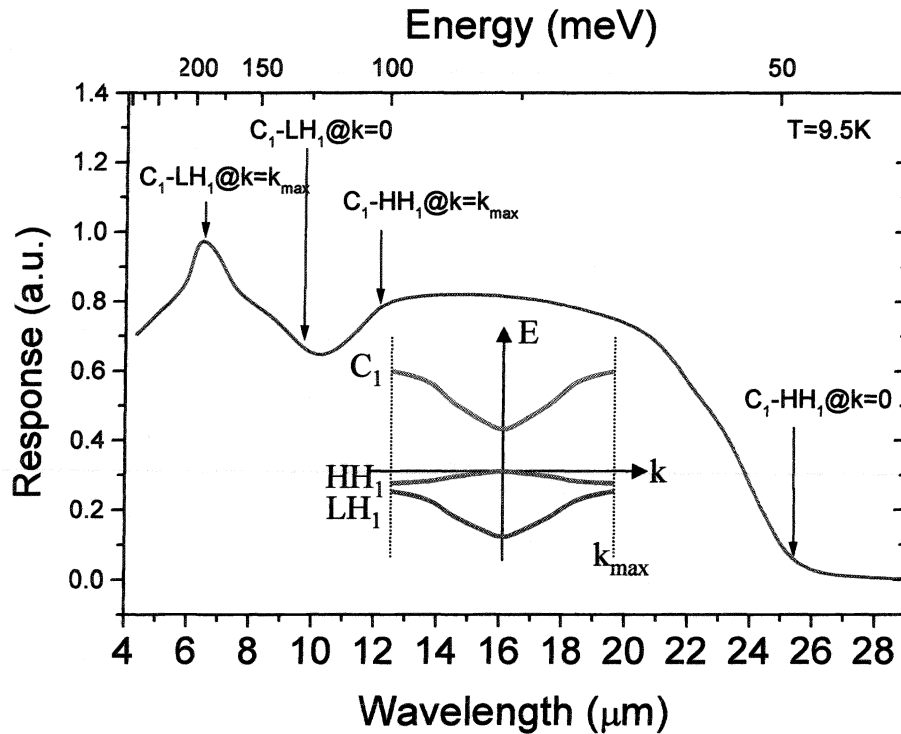


Fig. 4. The measured photoresponse of a p-i-n diode at $T=9.5\text{K}$ shows good agreement to the theoretically calculated transition energies at critical points.

4. TOWARD MINIATURIZATION

Although we could successfully reduce the Auger recombination rate by engineering the minibands of the superlattice and achieve a high detectivity, the Auger process is not completely eliminated yet. Figure 5 shows the energy dispersion of the minibands in the different momentum spaces. It is clear that the Auger recombination is not possible at $k_x=0$ and $k_y=0$, however because of the in-plane dispersion, the in-plane momentum of the electrons is not necessarily zero and hence Auger recombination is still possible.

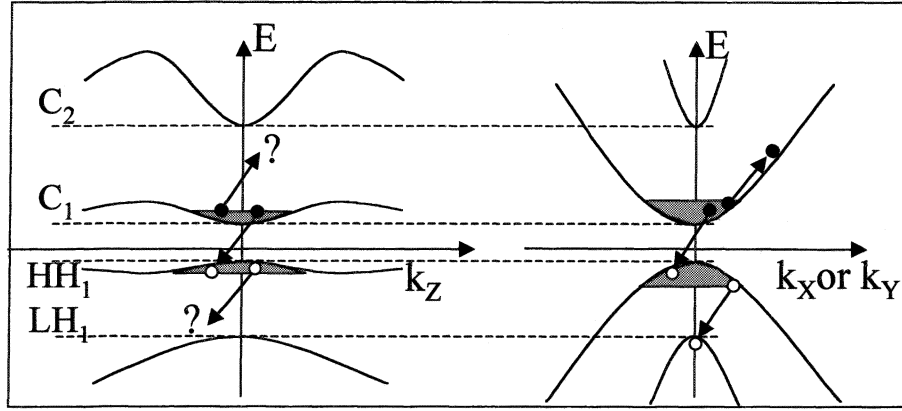


Fig. 5. The energy dispersion of the minibands in the different momentum spaces.

By inducing quantum confinement in the x and y directions, the dispersion in these directions can be quantized. This can totally eliminate the Auger recombination and hence the carrier lifetime will be limited by other mechanisms such as radiative and non-radiative recombination which are several orders of magnitude slower than the Auger recombination at room temperature.

$$\frac{1}{\tau_{\text{total}}} = \frac{1}{\tau_{\text{Auger}}} + \frac{1}{\tau_{\text{radiative}}} + \frac{1}{\tau_{\text{non-radiative}}} \quad (1)$$

Since the responsivity of the detector is proportional to the carrier lifetime as given in equation 2, the responsivity will also increase dramatically which in the absence of any noise enhancement, will lead to a much higher detectivity.

$$R_i = \frac{\lambda \eta q g}{hc}; g = \frac{\tau_{\text{total}} E(\mu_e + \mu_h)}{1} \quad (2)$$

We pursued a novel method which unlike the commonly used "self assembled" technique, can produce high quality, highly uniform quantum dot structures. The starting material is a superlattice grown similar to the above. Stacks of high quality quantum dots can be developed by etching pillars and consequent oxide coating. In order to achieve quantum size effect, one needs to confine the electrons within tens of nanometer. However, surface leakage current will be a severe problem for such a small device, since the ratio of the surface to the volume increases dramatically.

In order to circumvent this problem, we plan to use a gated device shown in figure 6. Although the diameter of the device is 50 to 200nm, the effective confinement diameter can be adjusted by the gate voltage to much smaller values. Moreover, the allowed energy states of the electrons can be changed by the gate voltage and hence the cutoff wavelength of the device.

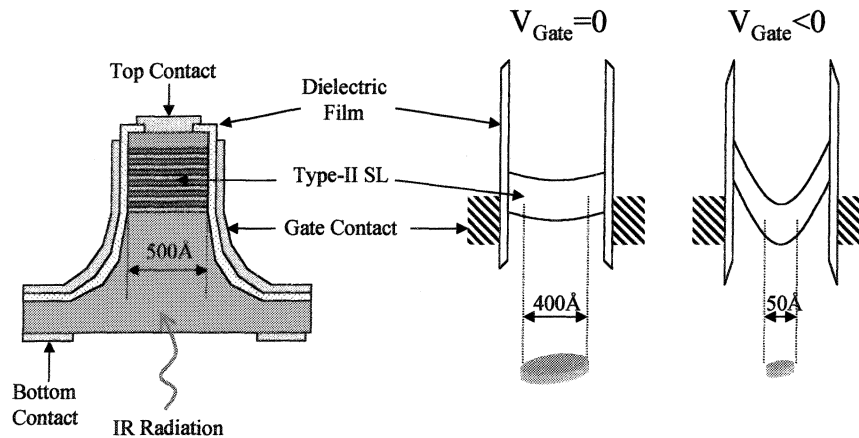


Fig. 6. Schematic diagram of the gated pillars with an adjustable lateral confinement.

The sensitive area of such quantum pillar is very small and not useful for many applications. Figure 7 shows the interconnection scheme which provides a large detector area using advanced metalization and passivation techniques.

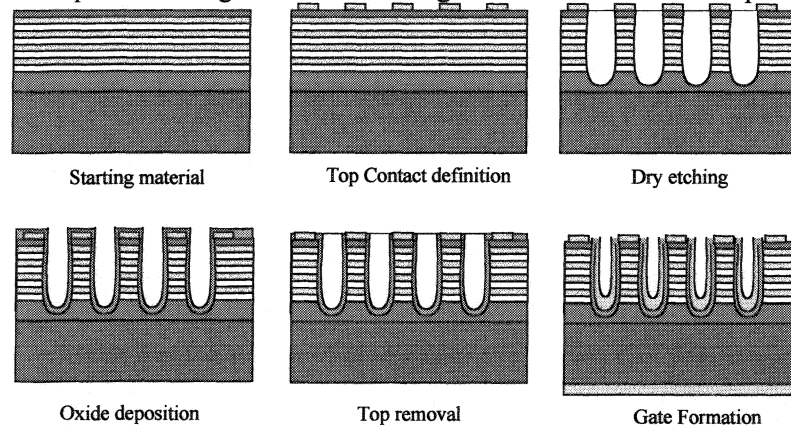


Fig. 7. Interconnection of the pillars with advanced metalization and passivation techniques.

Low energy e-beam lithography was used to produce top metal contacts. High quality metal contacts with diameter in the range of 1000 to 100nm were successfully defined on the surface of the samples as shown in figure 8. The aspect ratio of the metal contacts were from 1 to 10, showing the high flexibility of this technique.

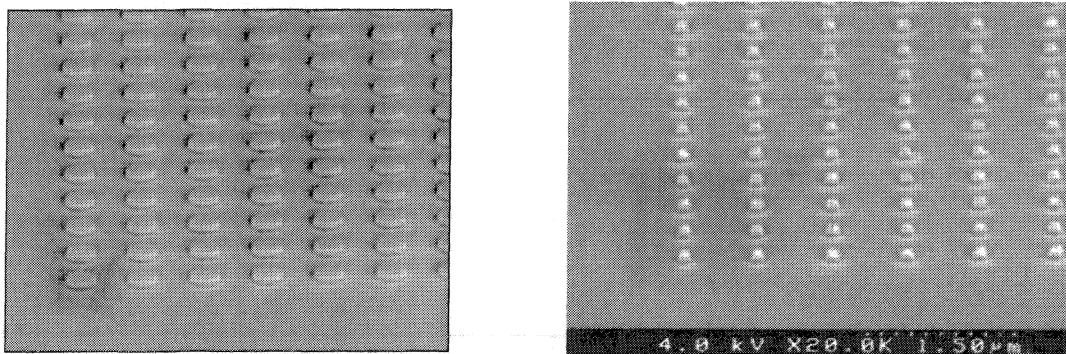


Fig. 8. Top metal contacts defined by e-beam lithography on top of the samples. (a) 500nm diameter contacts, and (b) 100nm contacts.

Reactive ion etching (RIE) was used to produce uniform anisotropic etching of the pillars through the material. The etching was designed for high ratio of vertical to horizontal etching rates. Figure 9 shows the results of such process on the 500nm diameter pillars. The vertical to horizontal ration is in excess of five. We managed to produce two dimensional arrays of this pillars with excellent uniformity over thousands of square micron.

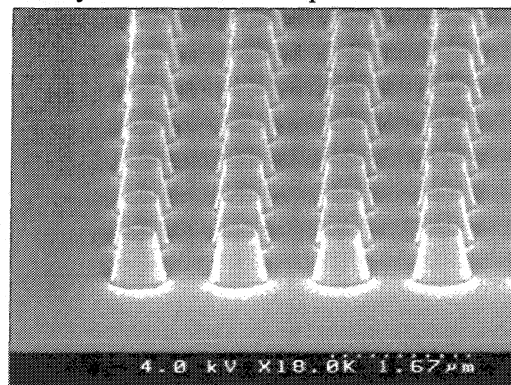


Figure 9. Reactive ion etching was used for the realization of uniform two dimensional arrays of pillars.

Passivation is one of the most important steps for the realization of these quantum devices. The key issues are the uniformity of the dielectric and the coverage of the device surface. We used plasma enhanced chemical vapor deposition (PECVD) techniques to form uniform layers of dielectrics. Figure 10 shows SEM image of a cleaved edge of a mesa covered with 50nm Si_3N_4 layer by this method.

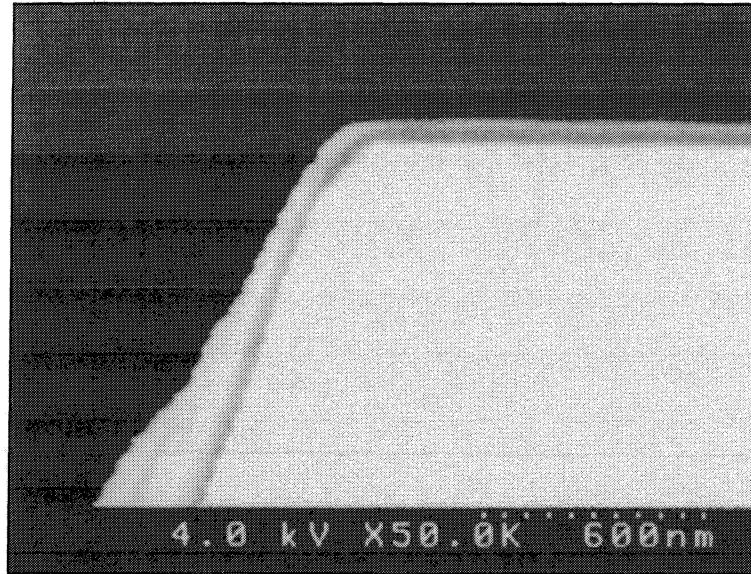
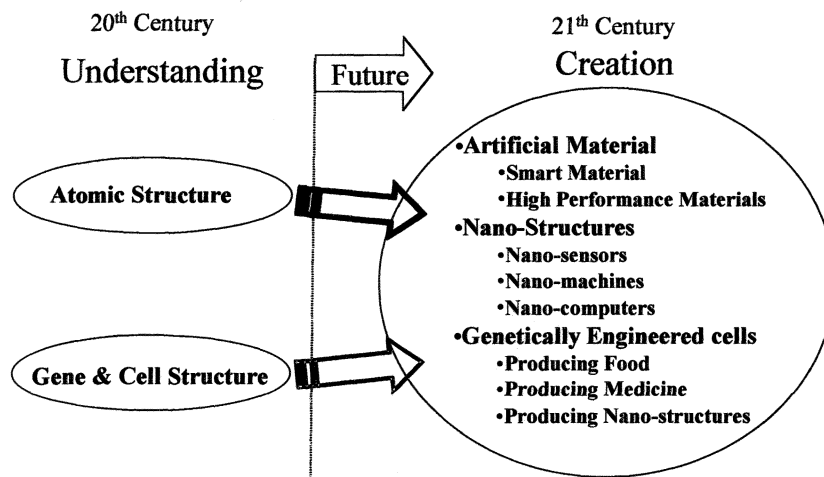


Fig. 10. SEM image of the cleaved edge of a mesa covered by a uniform layer of dielectric with a thickness of about 50nm.

5. CONCLUSION

The scientific and technological accomplishments of earlier centuries represent the first stage in the development of Natural Science and Technology, that of understanding. As the 21st century begins, we are entering the creation stage where promising opportunities lie ahead for creative minds to enhance the quality of human life through the advancement of science and technology.



Such efforts is exemplified in the development of high performance uncooled photon detectors. Using bandgap engineering, we designed type-II InAs/GaSb superlattices with a lower probability for Auger recombination which is the

most important recombination process at room temperature for the narrow gap material. The processed devices show an order of magnitude longer carrier lifetime compared to bulk material such as HgCdTe and InAsSb with similar bandgap due to the suppression of Auger recombination. This is a direct result of growing material with one dimensional confinement. Using advanced tools such as electron beam lithography and reactive ion etching, we plan to bring such enhancements to further steps by confining the motion of electrons in three dimensions. This can provide new generation of detectors with a much higher detectivity at room temperature as well as wavelength tunability in the near future.

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