Raith APPLICATION NOTE

Electron-beam lithography applications at ETH Zurich

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Introduction

Within the FIRST Center for Micro- and Nanoscience of the ETH Zurich, we use a RAITH150 electron beam lithography (EBL) system for a large palette of projects in photonics, electronics, material science, and physics. An overview of our main research activities in these fields is given below.

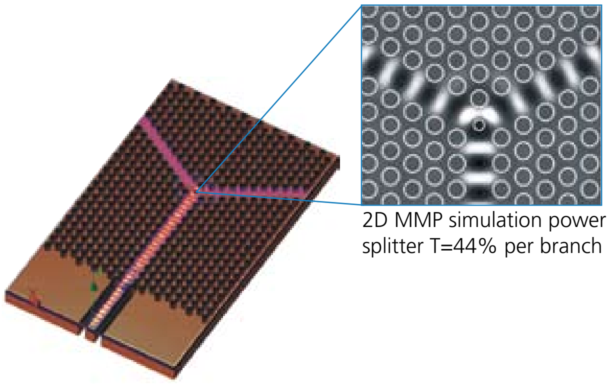
1. Photonics

InP-based photonic crystals

P. Strasser, R. Wüest, K. Rauscher, F. Robin, D. Erni, H. Jäckel, Communication Photonics Group, ETH Zurich

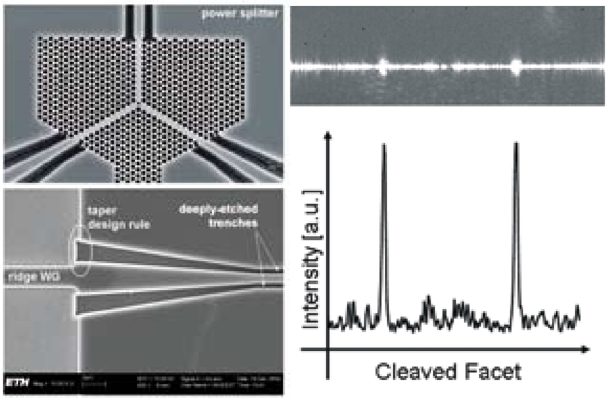
Thanks to their unique control of light, InP-based planar photonic crystals (PPCs) are a promising concept for the compact integration of passive and active optical functionalities. In InP-PPCs, vertical light confinement is ensured by an InP/InGaAsP/InP slab waveguide.

A triangular lattice of holes is etched deeply (> 3 µm) into the substrate using a combination of EBL and inductively coupled plasma reactive ion etching. Accuracy and reliability of the pattern transfer into the resist by EBL is ensured by using the NanoPECS software to correct for proximity effects. Devices are designed using 2D and 3D modelling tools and characterized using the End-Fire (port-to-port) technique and scanning near-field optical microscopy. We have for instance designed a PhC-based power splitter that theoretically demonstrates 42% transmission per branch and an excellent measured 50 / 50% power balance (figure 1).



2D MMP simulation power splitter T=44% per branch

3D FDTD simulation with InP/InGaAsP/InP vertical waveguide. T=42% per branch



Fabricated power splitter using e-beam & photolithography mix&match technology and ICP-RIE dry etching; measured device on the right side

Figure 1: Power splitter based on photonic crystal

2. Electronics

InP-based DHBTs for high-speed digital ICs

U. Hammer, J. Ruiz, I. Schnyder, F. Robin, H. Jäckel, Electronics Laboratory, ETH Zurich

For large-capacity communication networks requiring ultrahigh-speed electronic ICs, we pursue the design and fabrication of digital circuits. We are developing an InP-based double heterojunction bipolar transistor (DHBT) technology. Scaling the critical device dimensions into the sub-µm range is an important prerequisite for switching speeds beyond 100 Gb/s. We use a bilayer process, e-beam evaporation and lift-off to define emitter widths down to 200 nm.

We also are investigating the fabrication of a separated base contact to minimize the device parasitic capacitances. The vertical layer structure is optimized for speed, e.g., using an alternative base material such as GaAsSb to improve electron transport through the device. Prior to fabrication the device performance is modelled using 2D physical simulations. The DHBT-based circuits are characterized using mm-wave equipment for the +100 GHz range (figure 2).

InP HEMTs for low-noise amplifiers

R. Limacher, W. Bächtold, Lab. for Electromagnetic Fields and Microwave Electronics, ETH Zurich

Circuits based on InP High Electron Mobility Transistors (HEMTs) such as cryogenically-cooled low-noise amplifiers (LNAs) show the lowest noise and highest gain at microwave frequencies. We are involved in device and circuit design, modelling, fabrication and characterization of low-noise cryo-cooled amplifiers. Such circuits are used in the amplification chain for the radio-astronomy.

The fabrication of the T-shaped gate using EBL is a key step. In our standard process, the T-gate has a foot length of 200 nm, which results in a cut-off frequency f_T of 130 GHz and a minimum noise figure F_{min} of 0.8 dB at 20 GHz. We have designed 2-stages LNAs for the frequency ranges from 18 to 26 GHz and from 23 to 44 GHz that show gain in excess of 15.5 dB and 12.5 dB, and average noise figure of 2.35 dB and 2.6 dB (figure 3).

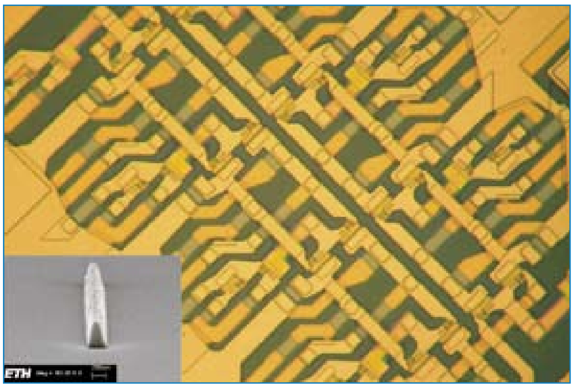
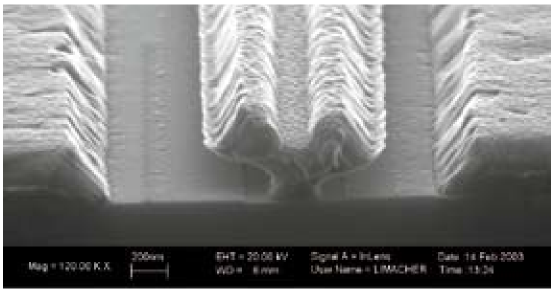
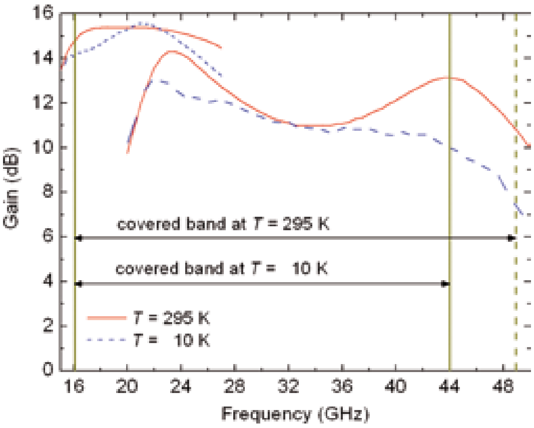
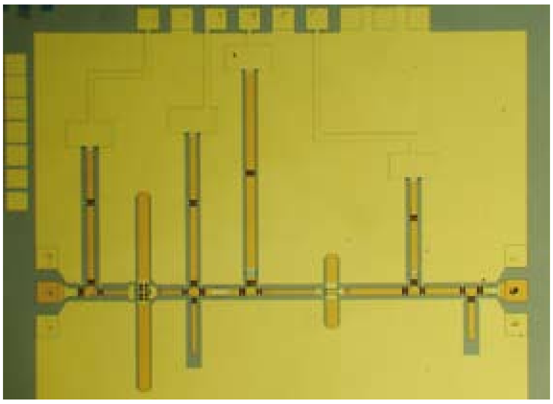


Figure 2: InP HBT-based ring oscillator IC with 0.7 µm emitter. 0.25 µm-wide emitter fabricated by EBL after metallization (inset)



High frequency transistor with T-gate





2-stages LNAs for frequencies from 18 - 26 GHz

Figure 3: Gain of 16-26 GHz and 23-44 GHz LNAs at 295 K and 10 K; T-gate and fabricated circuit

3. Quantum communication

Entanglement preservation in plasmon-assisted light transmission

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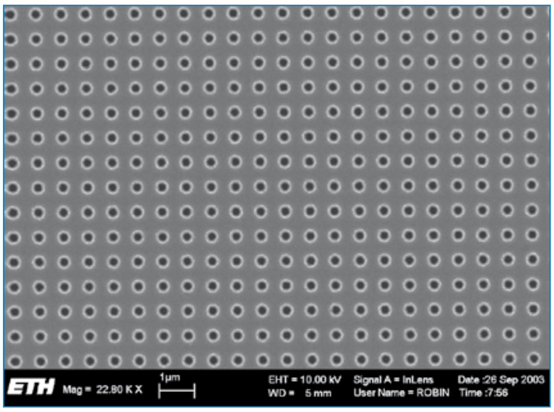
Energy-time entanglement (ETE) with photons at telecom wavelength is particularly efficient at carrying quantum information over optical fibers. However, entanglement involving solid matter is a mandatory step for useful quantum-information processing and storing. Interactions between 1.55 μm ETE photons and quantum states of matter are thus of great interest.

We investigate the coupling of ETE photons with surface plasmons (SP), a collective excitation wave involving electrons propagating at the surface of a metal layer. To this end, a perforated gold film is placed in the path of ETE photons. We have measured the strength of non-local quantum correlations whose strength is quantified by means of the visibility of interference fringes. When the perforated gold film is placed in the path of the ETE photons, a reduction of the visibility of the fringes is not observed, indicating that energy-time entanglement is preserved upon the photon-SP-photon conversion (figure 4).



Perforated gold film sample

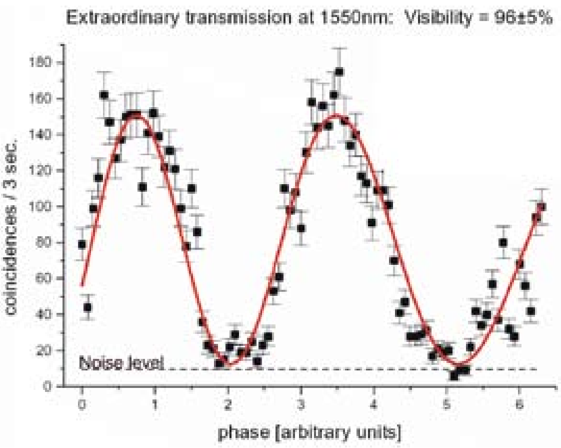


Figure 4: Interference fringes in the path of the photons

Quantum devices

C. Ellenberger, K. Ensslin, Lab. for Solid-State Physics, ETH Zurich

Qubits – the corresponding quantum information units for a classical bit – are at the heart of quantum-information processing devices. Controlling the spin of an electron trapped in a quantum dot is one way to implement them in solid-state devices. Quantum computation requires a full control of the individual qubits. Of particular interest, addressing and manipulating are still unresolved operations. In this project, we attempt to locally change the g-factor in order to separately address two qubits with different Zeeman energies. This eventually gives us the possibility to introduce separate spin-flips in the two dots with corresponding microwave pulses.

Electron beam lithography is used to define metallic top-gate structures to confine the underlying two-dimensional electron gas into the zero dimensional quantum dot (figure 5).

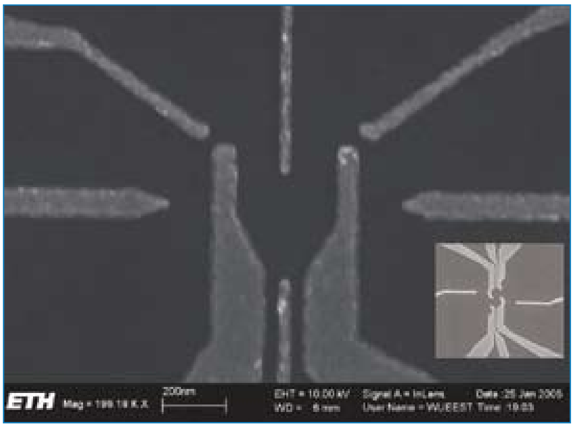


Figure 5: Few-electrons quantum dot for which single-electron trapping was demonstrated. Possible two-qubits device (inset)

Semiconductor nanowires

R. Leturcq, K. Ensslin, Lab. for Solid-State Physics,
C. Stampfer, Micro- and Nanosystems, M. Borgström,
J. Elzerman, A. Imamoglu, Quantum Photonics Group,
ETH Zurich

Of great interest for quantum information processing, semiconductor quantum dots allow the confinement and manipulation of single electrons. Conventional fabrication techniques are (i) self-assembled growth and (ii) lithographically-patterned electrodes defining the dot in a 2D electron gas. As an intermediate technique, semiconductor nanowires are promising because of their inherent lateral confinement. Furthermore they can be contacted electrically by means of lithography techniques. In this project, we contact the nanowires – grown using metal-organic vapor-phase epitaxy of III-V compounds – and define the quantum dot with a metallic gate or local oxidation. After growth, the nanowires are deposited onto a Si/SiO_2 substrate patterned with alignment markers, and SEM images are used to determine their relative position. Finally, the contacts are defined using EBL. Low-temperature measurements are performed to study the optical and electrical transport properties of the nanowires and the quantum dots (figure 6).

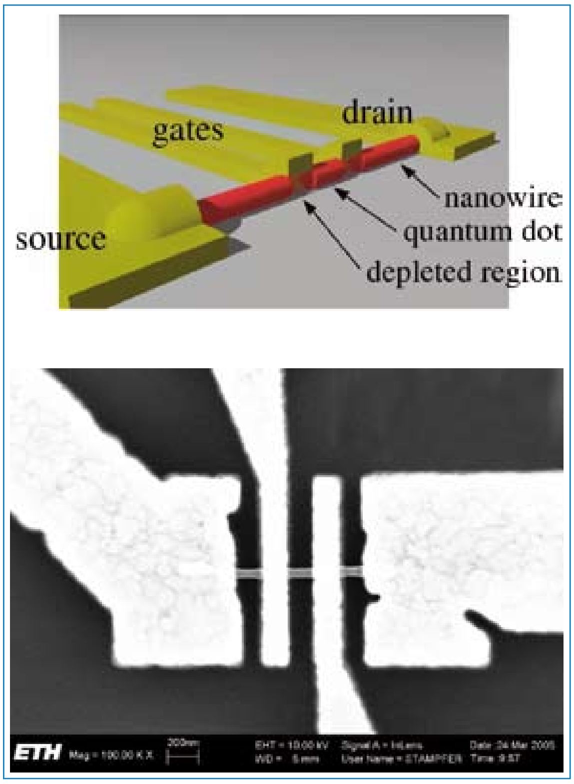
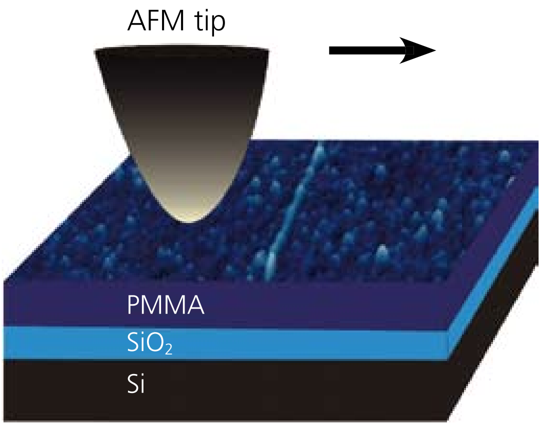


Figure 6: Electrical contacting of Nanowire (center) with source, drain and double-gate contacts

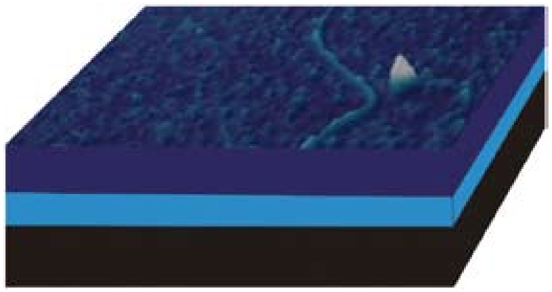
Quantum photonics

B. Babic, A. Badolato, A. Imamoglu, Quantum Photonics, ETH Zurich

Although optical properties of semiconducting single-walled carbon nanotubes (SWNTs) have been investigated, detailed quantum optical studies are still lacking. The investigation of the quantum dots formed by SWNTs helps us understanding their properties and potential applications. We will carry out a number of optical experiments on semiconducting carbon nanotube quantum dots, such as characterization of excitons and demonstration of photon antibunching (figure 7). A single quantum dot (QD) in a nano-cavity is a powerful device for exploring cavity quantum-electrodynamic (QED) effects and provide a building block for experiments in quantum computation. Similar structures can also be used to induce controlled interactions between spins. In collaboration with the University of California in Santa Barbara (UCSB), we demonstrated a new approach to QD cavity-QED which solves both the spatial and spectral overlap problems and realizes deterministic coupling of any given QD line to a GaAs high-Q photonic crystal (PC) defect cavity mode. We will fabricate such 2D PC structures with an actively positioned QD to generate entangled photons and spins.



Before manipulation



After manipulation

Figure 7: Manipulation of CNT using AFM

4. Nanotubes and nanowires

Electricomechanical properties of CNTs

C. Stampfer, A. Jungen, C. Hierold, Micro- and Nano-systems, ETH Zurich

We explore the properties and the potential use of single-walled carbon nanotubes (SWNT) as active elements in future nano-electromechanical systems (NEMS). This is a first step into the field of SWNT-based nano systems providing a foundation for future research in nano system transducers. The exceptional electrical, mechanical and electromechanical properties of SWNTs make them promising candidates for future sensing elements.

We focus on the integration of carbon nano-structures with state-of-the-art micro-machining techniques. We established a fabrication process for nanoscaled Au bridge and cantilever-based transducers with integrated SWNTs. Atomic Force Microscope (AFM) based force vs. deflection measurements have been performed to characterize these devices. Mechanical and electromechanical measurements are used to study the functionality of the device with or without integrated SWNTs (figure 8).

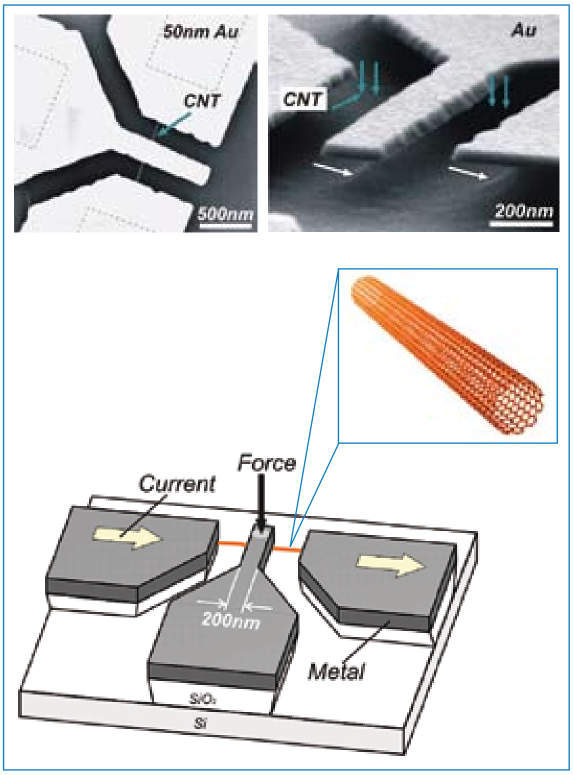


Figure 8: Cantilever-based nanotransducer with integrated SWNT
Upper left: SEM top view
Upper right: SEM side view
Bottom: Schematics

Mechanical properties of CNTs

A. Subramanian, B. Nelson, IRIS, ETH Zurich

Nano-scale devices are being investigated for use in diverse applications such as mass, force or position sensing. These devices are expected to enable bio-microrobotic exploration. We focus on building such nano-robotic devices and nano-electromechanical systems (NEMS) but also on developing tools essential for the fabrication, assembly and characterization of NEMS. In particular, horizontal and vertical multi-walled carbon nanotube (MWNT) arrays are investigated for use as electromechanical components due to their exceptional mechanical and electrical properties. Vertically-aligned arrays are fabricated using a combination of EBL and PECVD growth of MWNTs (Nanolab Inc., USA). These arrays have been employed to realize nano-scale encoders. Laterally-aligned arrays of MWNTs are fabricated combining electron beam lithography and dielectrophoretic (DEP) assembly techniques. These arrays are investigated for use in lateral emission applications (figure 9).

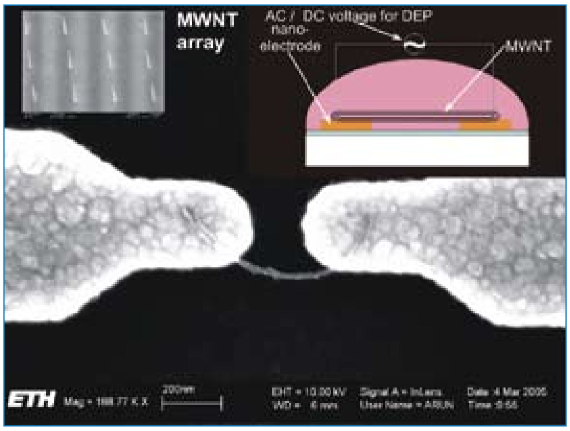


Figure 9: Individual MWNT after DEP, array of MWNTs (leftinset), principle of DEP-based assembly of individual MWNTs (right inset)

Mechanical properties of metallic nanowires

S. Olliges, R. Spolenak, Lab. for Nanometallurgy,
M. Leibinger, FIRST lab., ETH Zurich

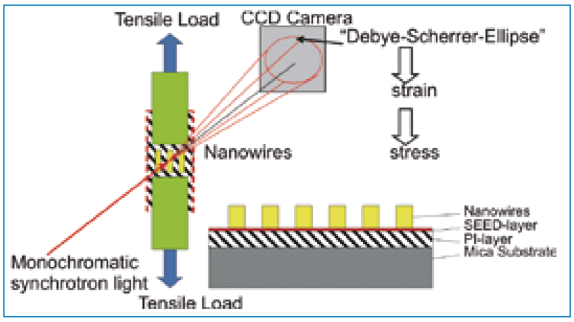


Figure 10: Setup for the measurement of mechanical properties of nanowires

The mechanical properties of metallic nanowires are investigated by SEM, TEM and synchrotron-based tensile testing techniques. These wires are expected to reach their shear strength and undergo phase transformation as a function of their diameter. To investigate the properties of the nanowires, a µm-thick polyimid layer is deposited on a mica substrate to facilitate detachment. After metallization and spinning on PMMA, 1–3 pixel-wide lines are written using electron beam lithography to fabricate 10-50 nm-wide and 1 mm-long wires. The grooves are subsequently filled using Au electroplating. Finally, the residual PMMA and the mica substrate are removed.

The residual stress measurement is done by X-ray diffraction using the $\sin^2(\psi)$-technique whereas the $\sin^2(\varphi)$-technique is applied for the tensile load experiments. The differential stresses depending on the in-plane angle φ are obtained by the difference between the Debye-Scherrer circles and the unloaded Debye-Scherrer ring. The investigations are performed at the Surface Diffraction Beamline of the Max-Planck-Institut für Metallforschung at ANKA, Forschungszentrum Karlsruhe, and the MS Powder Beamline at the Swiss Light Source, PSI, Villingen (figure 10).

5. Superconducting Single Photon Detectors

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Physics Institute, University of Zürich

Superconducting single photon detectors are powerful devices as they are ultra sensitive and are able to detect a wide range of the electromagnetic spectrum with higher count rates than semiconducting detectors. They may find applications in such diverse fields as device testing, infrared astronomy and planetary missions, telecommunication, quantum cryptography and x-ray spectroscopy. In order to improve the detector performance, the width of the meander bridges needs to be decreased as much as possible while retaining high uniformity. The Raith EBL system is used to define the photon detector in a simple lift-off process with PMMA 950k. The figure 11 shows the principle design of our detector structure. The shown meander covers an area of 4 by 4 microns. The bridge is 100 nm wide. Figure 12 shows a first result of straight lines with lateral dimensions as small as 10 nm.

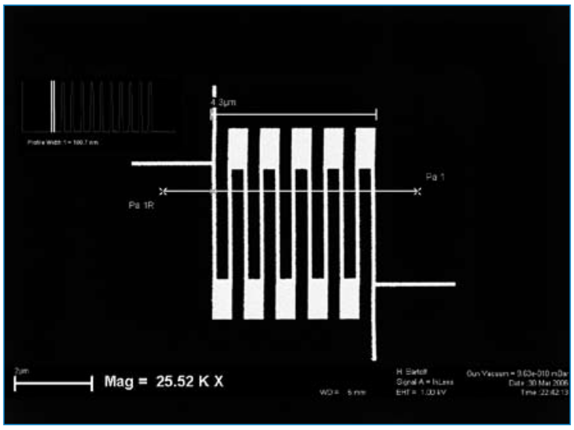

Figure 11: Principle design of detector structure

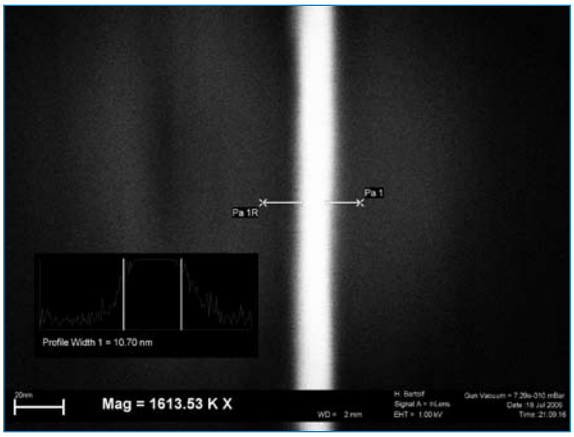

Figure 12: Straight line with lateral dimensions