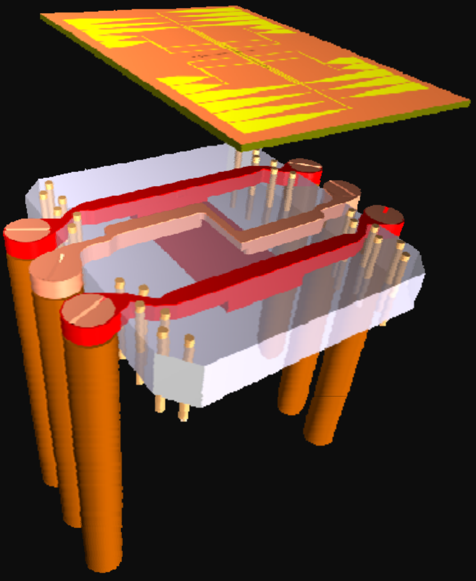
Atom Chips



Jörg Schmiedmayer
Atominstitut der Österreichischen Universitäten, TU-Wien
www.atomchip.org

THE VISION
Atom Chip

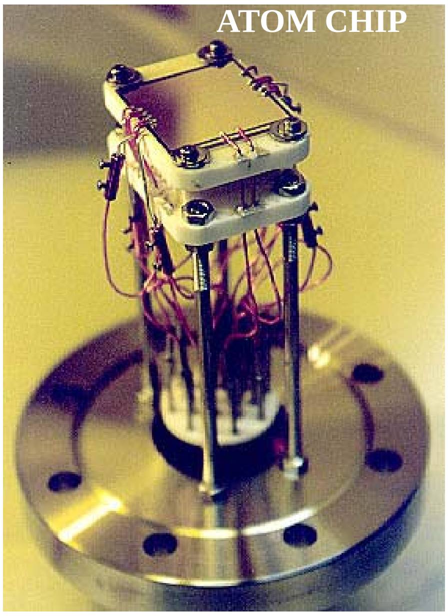
neutral-atom manipulation using integrated micro-devices

combining the best of two worlds:

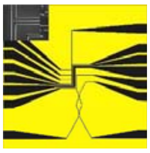
- **cold neutral atoms** - a well controllable quantum system
- technologies of **nano-fabrication, micro-electronics, micro-optics**

Take the tools of quantum optics and atomic physics and make them robust and applicable by miniaturizing and integrating them using the techniques of nano-fabrication, micro-electronics and micro-optics.

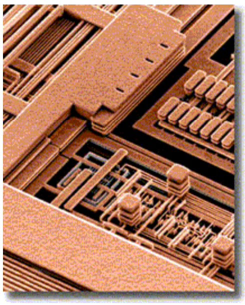
- create a **tool box** for building quantum devices



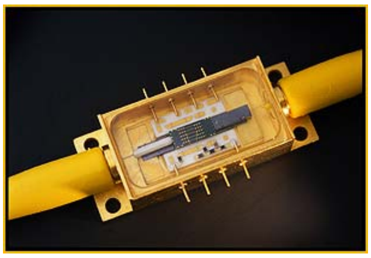
MINIATURIZATION and INTEGRATION



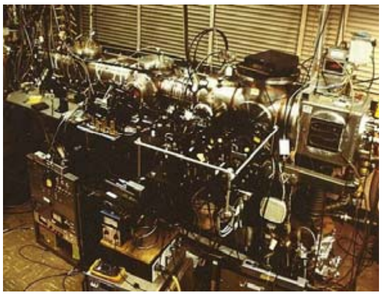
Electronics

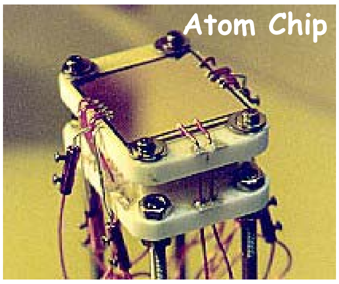


Optics

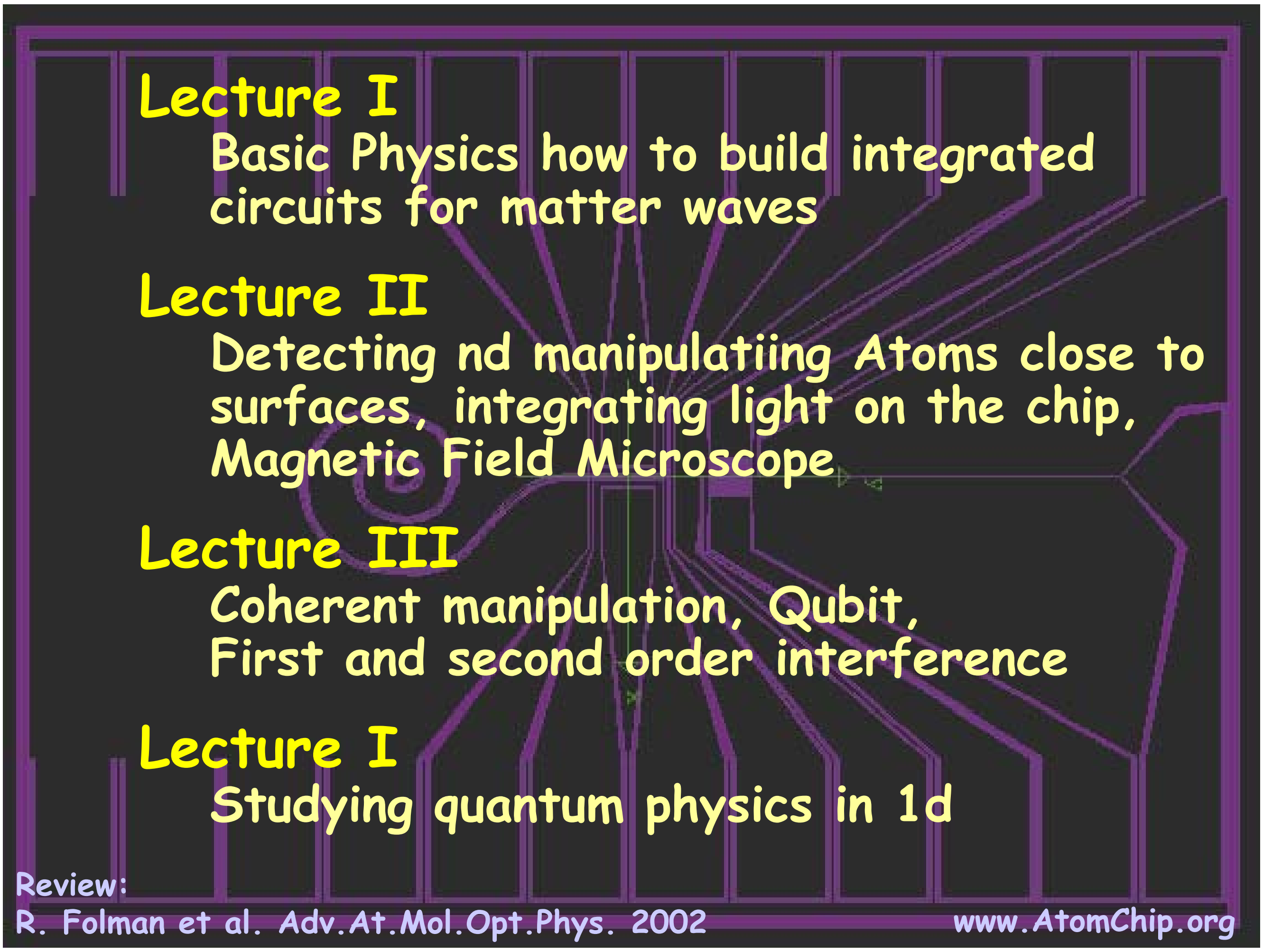


Matter waves





mesoscopic matter wave optics similar to quantum electronics



Lecture I

Basic Physics how to build integrated circuits for matter waves

Lecture II

Detecting nd manipulatiing Atoms close to surfaces, integrating light on the chip, Magnetic Field Microscope

Lecture III

Coherent manipulation, Qubit,
First and second order interference

Lecture I

Studying quantum physics in 1d

Review:
R. Folman et al. Adv.At.Mol.Opt.Phys. 2002

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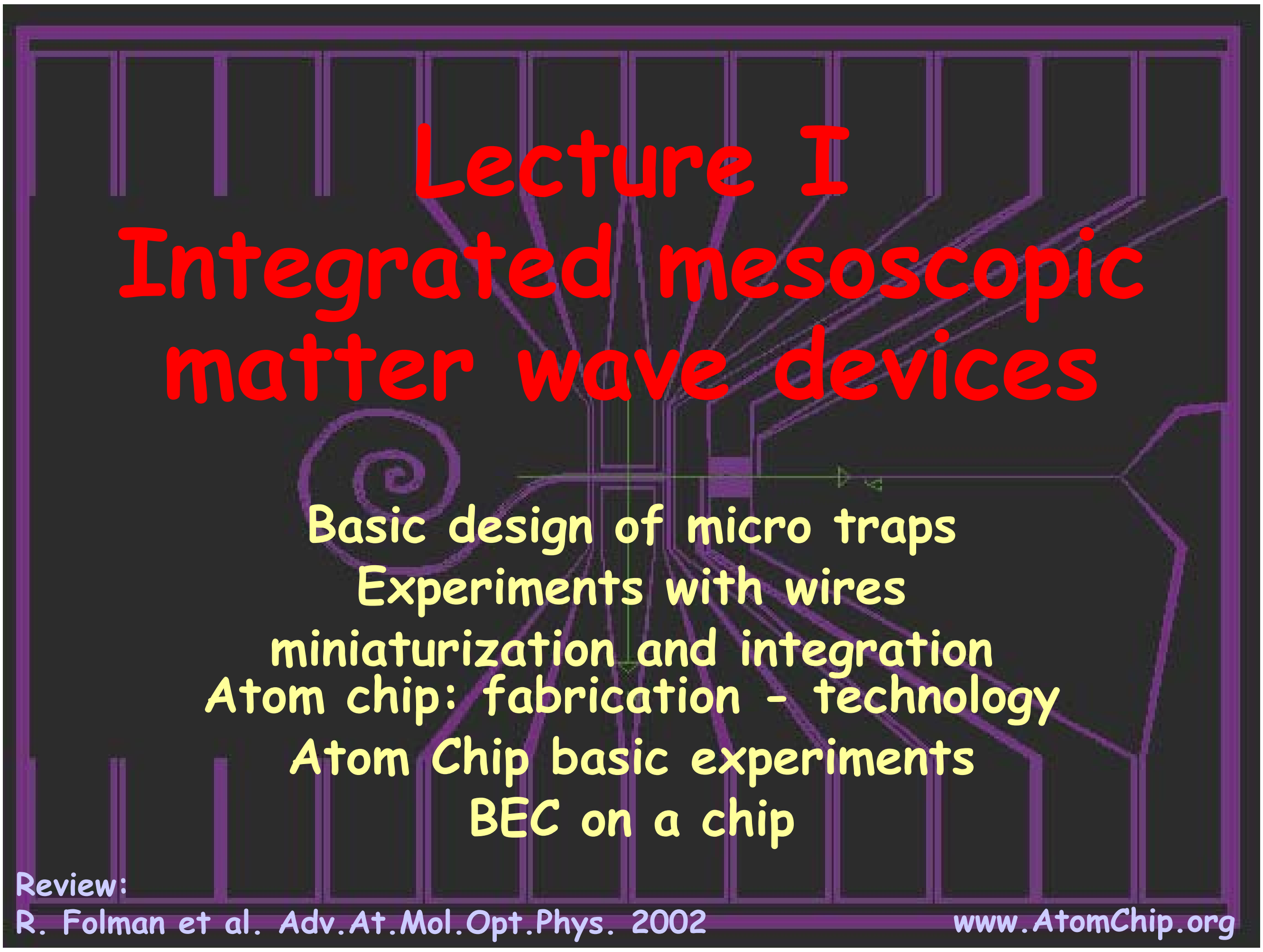


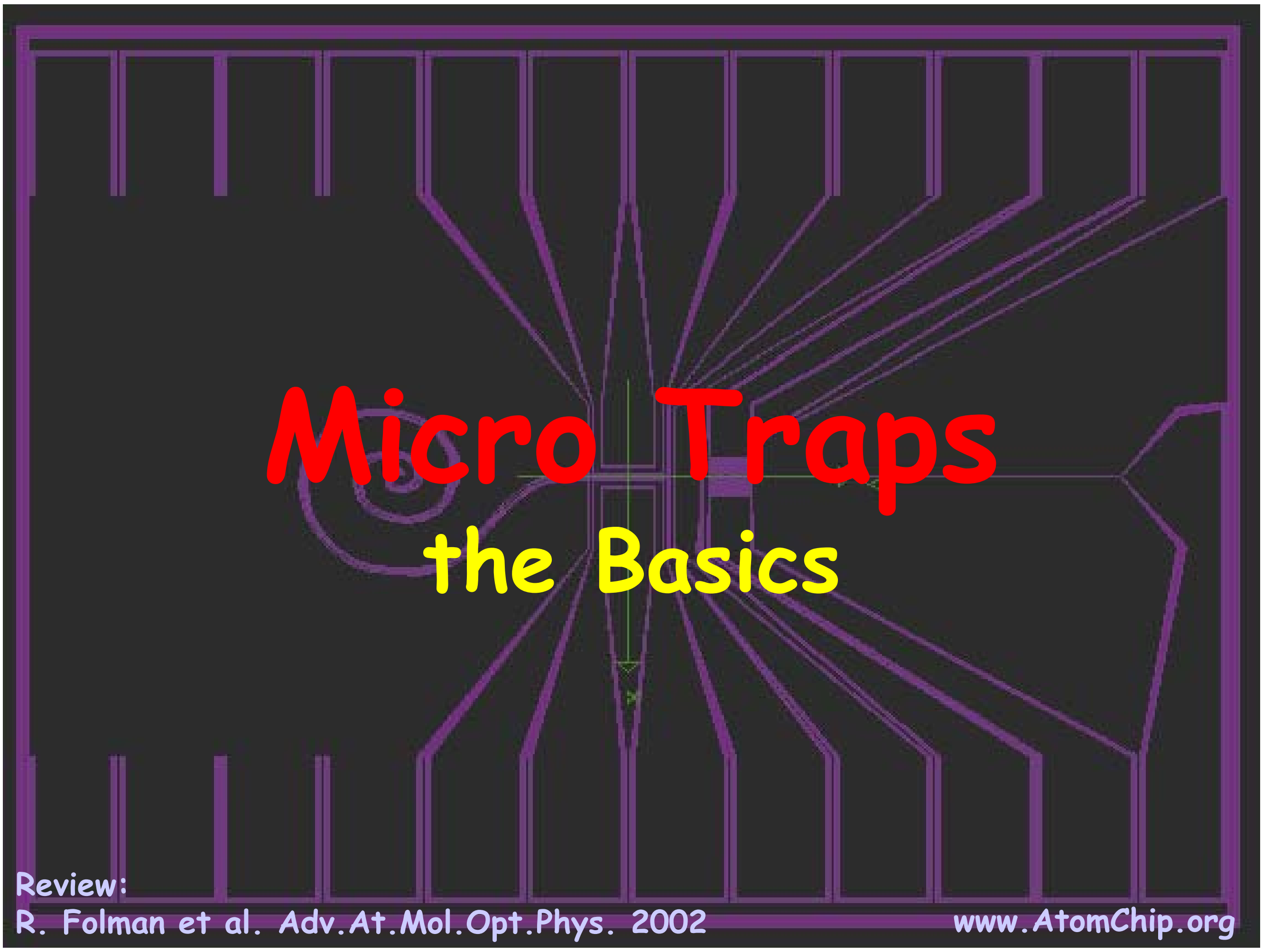
Lecture I

Integrated mesoscopic matter wave devices

Basic design of micro traps
Experiments with wires
miniaturization and integration
Atom chip: fabrication - technology
Atom Chip basic experiments
BEC on a chip

Review:
R. Folman et al. Adv.At.Mol.Opt.Phys. 2002

www.AtomChip.org



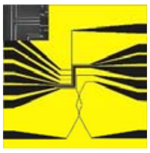
Micro Traps

the Basics

Review:
R. Folman et al. Adv.At.Mol.Opt.Phys. 2002

www.AtomChip.org

Interactions for neutral atoms



Magnetic Potentials

Magnetic moment of the atom interacting with the magnetic field

$$U_{mag} = -\vec{\mu} \cdot \vec{B}$$

$U_B[\mu K] \propto 67\ B \quad [G]$

strong field seeker: $U_{mag} < 0$
weak field seeker: $U_{mag} > 0$

Electric Potentials

Electric polarizability interacting with an electric field

$$U_{el} = -\frac{1}{2} \alpha E^2$$

Li-Atom: $\alpha = 24 A^3$

$U_E[\mu K] \propto 98\ E^2 [V/\mu m]$

Dressed State Potentials

coupling of two internal states by an external oscillating field.

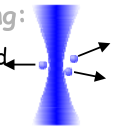
Optical Dipole Potentials:

coupling ground and electronically excited states with laser light, far detuned from resonance to prevent spontaneous scattering

-> potentials is proportional to local intensity.

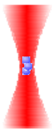
$$U_{dip} \propto -\alpha(\omega) I(\vec{r})$$

Blue detuning:



Atoms repelled from intensity maxima

Red detuning:



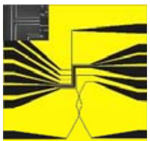
Atoms trapped in intensity maxima

RF Dressed State Potentials:

Coupling electronic ground states of an atom by magnetic RF. Coupling strength and detuning shapes the potential.

MAGNETIC INTERACTION

$$U_{mag} = -\vec{\mu} \cdot \vec{B}$$



IBK, HD

Vladimirskii Sov. Phys. JETP 12, 740 (1961)
Experiment: Schmiedmayer IQEC 92; PRA 52, R13 (1995)
Denschlag et al. PRL 82, 2014 (1999)

Quantum wire:

current carrying wire

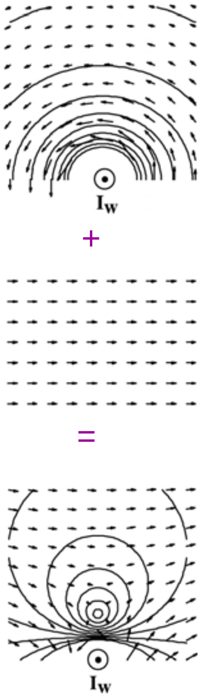
$$\vec{B}(\rho) \propto I \frac{1}{\rho} \hat{e}_\varphi$$

Vector Coulomb Problem

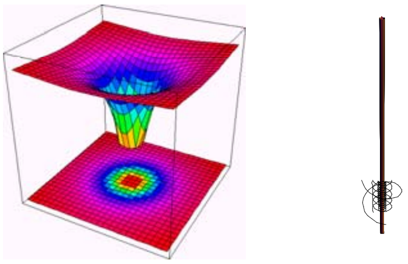
adding a bias field creates a potential minimum on side of wire (Frisch, Segre 1932)

Potential
- depth: bias field
- minimum: angle current<-> field
- gradient: $1/I$

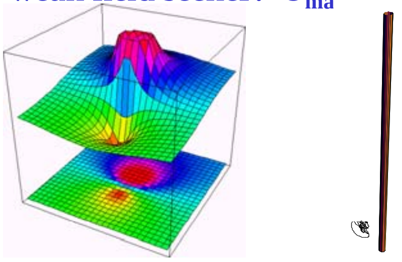
Mount wire on a surface:
Use nanofabrication to build mesoscopic structures.



strong field seeker: $U_{mag} < 0$



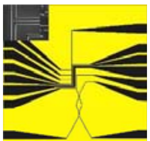
weak field seeker: $U_{ma} > 0$



Achievable: level spacing of up to MHz

MAGNETIC INTERACTION

$$U_{mag} = -\vec{\mu}\cdot\vec{B}$$



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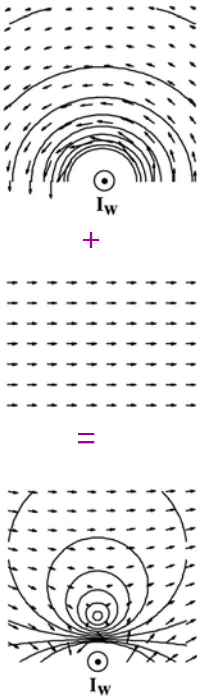
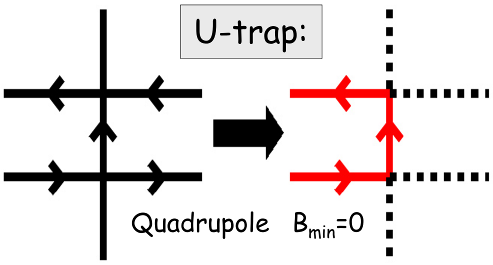
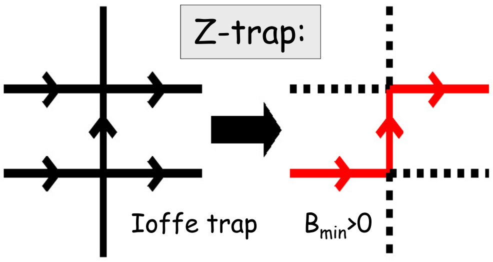
Mount wire on a surface: Use nanofabrication to build mesoscopic structures.





U-trap:

Quadrupole $B_{min}=0$

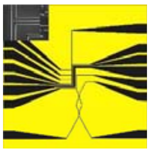


Z-trap:

Ioffe trap $B_{min}>0$

Achievable: level spacing of up to MHz

Magnetic potentials
scaling



scaling for the mag. field of a wire

magnetic field:	r^{-1}
gradient:	r^{-2}
curvature:	r^{-3}

Wire guide:
- Distance from Wire $$r_0 = \frac{\mu_0}{2\pi}\frac{I_w}{B_b} \qquad B_0 = \frac{\mu_0}{2\pi}\frac{I_w}{r_b}$$
- Gradient of quandrupole scales like $$\left.\frac{dB}{dr}\right|_{r_0} = \left(\frac{2\pi}{\mu_0}\right)\frac{B_b^2}{I_w} = \frac{B_b}{r_0}.$$
- The zero in the centre can be removed by adding a longitudinal field B_{ip}

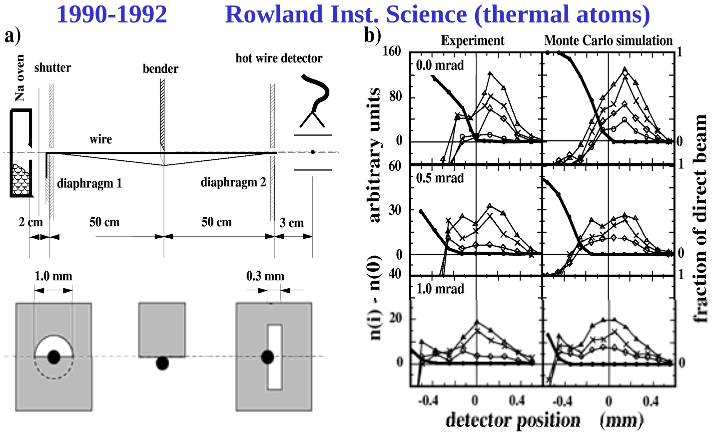
curvature scales like: $$\left.\frac{d^2B}{dr^2}\right|_{r_0} = \left(\frac{2\pi}{\mu_0}\right)^2\frac{B_b^4}{B_{ip}I_w^2} = \frac{B_b^2}{r_0^2 B_{ip}}.$$

trap frequency: $$\frac{\omega}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{\mu_B g_F m_F}{M}\left(\frac{d^2B}{dr^2}\right)} \propto \frac{B_b}{r_0}\sqrt{\frac{1}{MB_{ip}}},$$

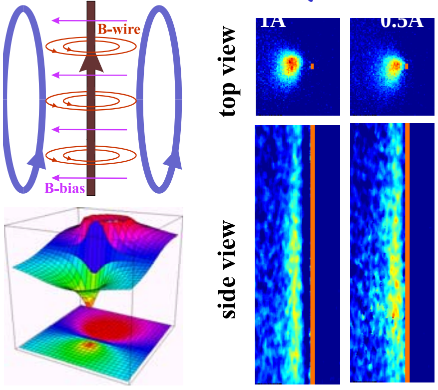
ATOMS and WIRES
microscopic guides and traps

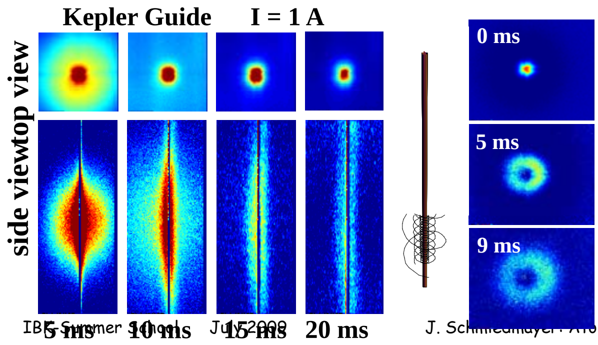
Innsbruck

1990-1992 **Rowland Inst. Science (thermal atoms)**



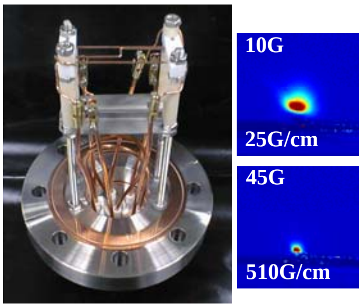
1995-99 **Innsbruck (cold atoms)**





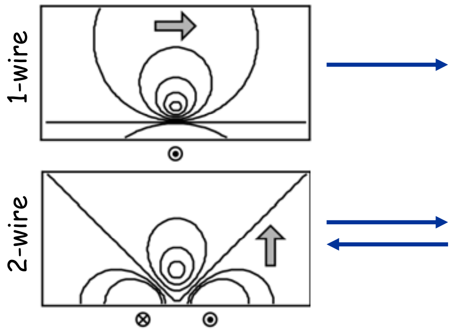
Schmiedmayer **IQEC 92**;
PRA **52**, R13 (1995)
Denschlag et al. PRL **82**, 2014 (1999)
Appl.Phys. B **69** 291 (1999)
A. Haase Diplomarbeit (2000)

Z-trap

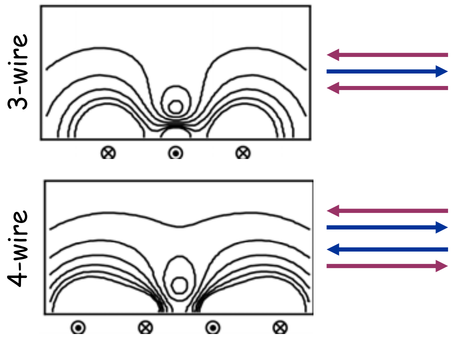


DESIGNS
Surface Mounted Atom Optics

Guides
with external bias field

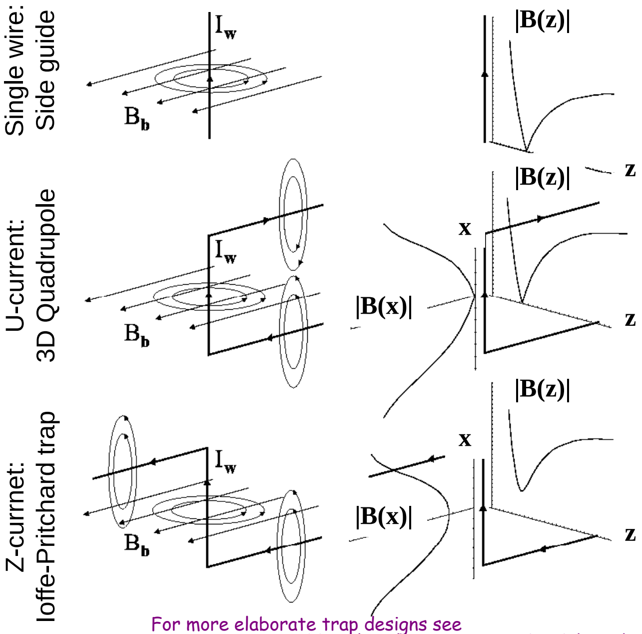


with on chip bias field



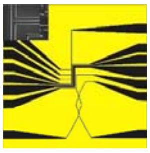
See also: J.H. Thywissen et al., EPJ D **7**, 361 (1999)

How to build a trap
minimum of the potential is given by the angle between the wire and the bias field

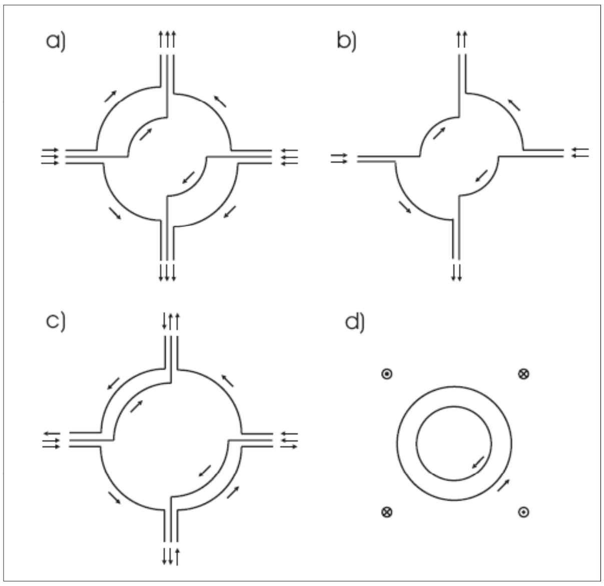


For more elaborate trap designs see
J. Weinstein, K. Libbrecht, Phys.Rev. A 52, 4004 (1995)

Magnetic trapping
designs

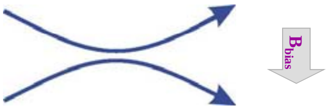


Planar trap designs

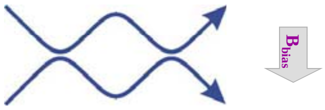


J. Weinstein, K. Libbrecht, Phys.Rev. A 52, 4004 (1995)

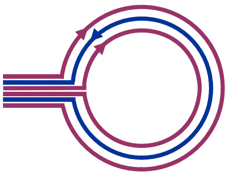
- **Beam Splitter**



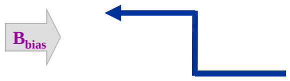
- **Interferometer**



- **Ring**



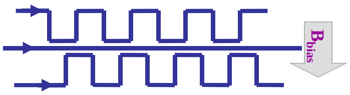
- **Trap**



- **Array**

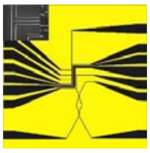
Rotating bias field produces a moving array

- **Shiftregister**



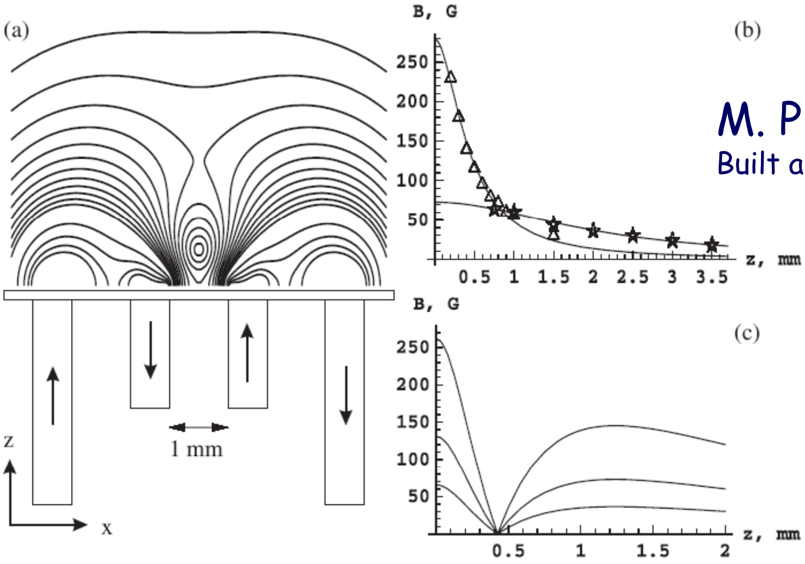
alternating current through the upper and lower meander with a 90 deg. phase shift produces a moving potential
W. Hansel, et al., PRL **86**, 608 (2001)

Magnetic Traps
permanent (fabricated) micro magnets



Harvard

Magnetic potentials of micro magnets



M. Prentis
Built a storage ring

See also: Posters from the groups of: E. Hinds @ IC and R. Spreuw @ Amsterdam

ELECTRIC INTERACTION

$$U_{el} = -\frac{1}{2}\alpha E^2$$

IBK, HD

Denschlag et al. EPL 38, 405 (1997)
Denschlag et al. PRL 81, 737 (1998)

Quantum wire:

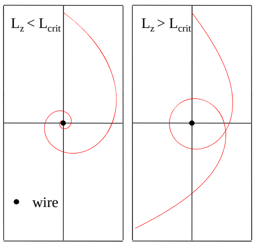
Charged wire

$$U_{el} \propto -\frac{\alpha q^2}{\rho^2}$$

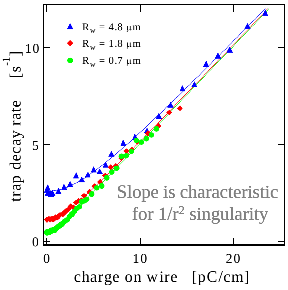
1/r² singularity

Classical Trajectories

no stable orbits!



Fall into the singularity



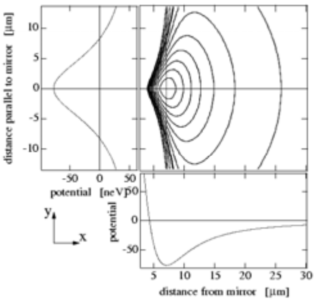
Slope is characteristic for 1/r² singularity

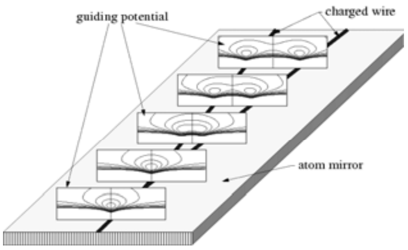
mount on an atom mirror

$$U_{mirror} \propto e^{-\kappa_m z}$$

atom is guided in potential minimum above the surface of the atom mirror

Use nanofabrication to build mesoscopic structures.





Schmiedmayer EPJ D 4, 57 (1998)

Achievable: level spacing of >1 MHz

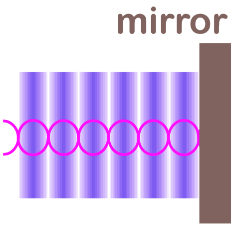
Optical Traps on Atom Chips

implement Feshbach Physics on the Chip

Heidelberg

Enhance the versatility of the Atom Chip by combining electric and magnetic potentials with optical dipole potentials

Use reflective properties of Atom Chip for 1D, 2D and 3D standing-wave-potentials



For large detuning

$$U(x) = \frac{\hbar\Omega_0^2}{4\Delta}\left(1+\cos\vec{G}\vec{x}\right)$$

Modulate ***magnetic*** **traps** using *optical* potentials (Optical lattice QIP on chip)

Modify ***optical*** **traps** with *magnetic (electric)* potentials

- The **trapping** potential is created by an **optical dipole potential**, for example a standing wave creates a 2d quantum well
- Create additional **structure** using **electric** and **magnetic** interactions coming from the chip similar to the gates … in quantum electronics.

These traps have many advantages

- **State independent** traps if structured by **electric fields**
- **State dependent** traps if structured by **magnetic fields**
- Trapping in the **absolute ground state**
- Local **feshbach resonances**
- Possibility to use **high resistivity atom chips** which reduce the de-coherence from Johnson noise.

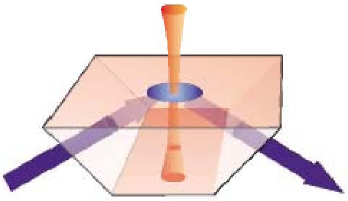
Structure the dipole traps by holographic means (spatial light modulators)

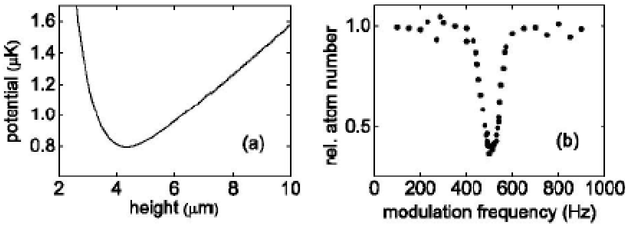
Gravito-Optical Surface Trap
2-dim quantum gas

IBK, Grimm

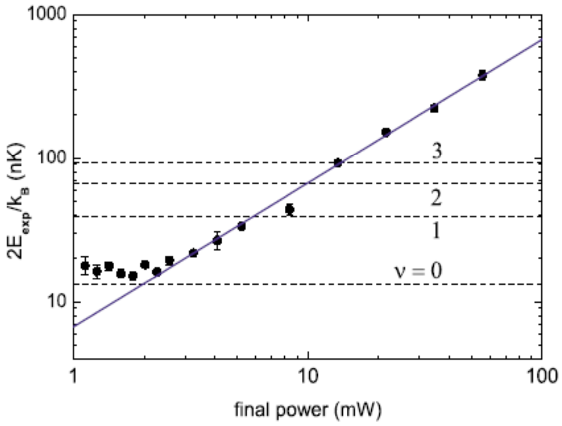
Cs atoms trapped above an surfave, confined by gravity and the evanescent wave mirror, transversal confinement by a dipol trap beam

Experimental setup





Cooling to the lowest energy level



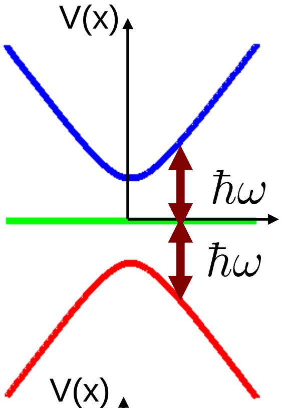
Details see the poster by S. Engeser

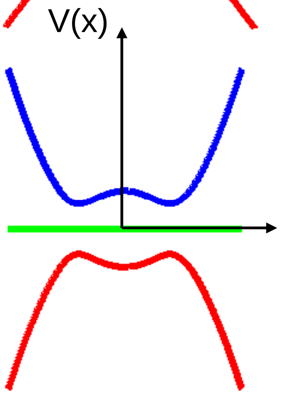
D. Rychtarik et al. PRL **92**, 173003 (2004)

Adiabatic Potentials
RF and MW dressing

create adiabatic dressed state potentials by coupling electronic ground states

- coupling between stable states allows to create conservative potentials even with on resonant radiation
- shaping the potential:
  - detuning the states with an external magnetic field
  - spatial dependent coupling strength (RF field) -> allows strong field seeker traps
- coupling is magnetic: the amplitude and the relative orientation of the RF field and the detuning field are important





– First ideas, spectroscopy	C. Cohen Tannudji, S. Haroche (1970's)
– first experiment: dressed neutrons:	E. Muskat et al., PRL **58**, 2047 (1987).
– first proposal of a MW trap (detuned)	C. Agosta, et al. PRL. **62**, 2361 (1989).
– MW experiment (Cs, detuned)	R. Spreeuw, et al. PRL **72**, 3162 (1994).
– RF dressed state traps (with magnetic field detuning but neglecting polarization)	O. Zobay, B. M. Garraway, PRL **86**, 1195 (2001).
– RF potentials for thermal Rb atoms:	Y. Colombe, et al. Europhys. Lett. **67**, 593 (2004).
– Full implementation	T. Schumm et al Nature Physics **1**, 57 (2005)

Adiabatic Potentials
RF and MW dressing

Oscillating RF magnetic field

$$\mathbf{B}_{RF}(\mathbf{r},t) = \frac{B_{RF}}{\sqrt{2}}\left[\mathbf{e}_x \cos(\omega t) + \mathbf{e}_y \cos(\omega t + \delta)\right]$$

relative phase shift

Total Hamiltonian

$$H = \frac{\mathbf{p}^2}{2M} + g_F \mu_B \mathbf{F}\cdot\left[\mathbf{B}_S(\mathbf{r}) + \mathbf{B}_{RF}(\mathbf{r},\omega t)\right]$$

1. apply the unitary transformation $U_S(\mathbf{r})$ to diagonalize the static part
2. transform into a rotating frame around the local quantization axis
3. perform the rotating-wave-approximation
4. diagonalize spin-field interaction terms

$$H_{\mathrm{final}} = \frac{1}{2M}\left[\mathbf{p} + \cancel{\mathbf{A}'(\mathbf{r},t)}\right]^2 - \frac{1}{2M}\cancel{\Phi'(\mathbf{r},t)} + \boxed{g_F\mu_B|\mathbf{B}_{\mathrm{eff}}(\mathbf{r})|F_z}$$

adiabatic approximation

dressed adiabatic potentials

B_{eff} does not necessarily obey Maxwell's equations

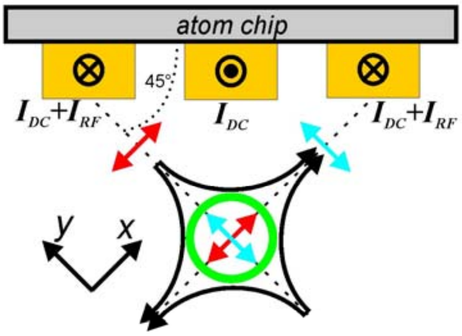
- potential depends on the relative orientation of the RF and the static field
- spatial dependence gives rise to novel types of RF traps
- free parameter d, i.e. RF polarization can be used to modify the trap shape

theory: I. Lesanovsky et al. PRA **73** 033619 (2006)
I. Lesanovsky et al. PRA **74** 033619 (2006).

experiment: T. Schumm et al. Nature Physics **1**, 57 (2005)
S. Hofferberth et al. Nature Physics **2**, 710 (2006)

RF induced Potentials
state dependent potentials by RF polarization

Polarization of the RF field gives extra freedom

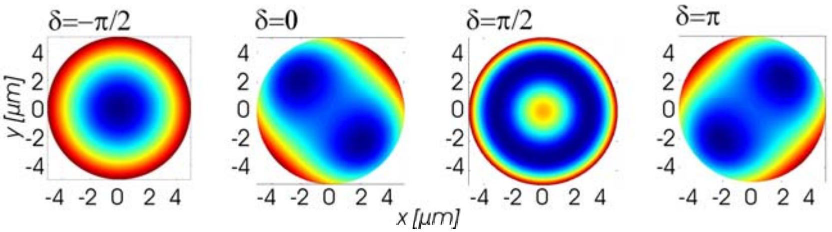


$$\mathbf{B}_S(\mathbf{r}) = Gx\mathbf{e}_x - Gy\mathbf{e}_y + B_I\mathbf{e}_z$$

$$\mathbf{B}_{RF}(\mathbf{r},t) = \frac{B_{RF}}{\sqrt{2}}\left[\mathbf{e}_x\cos(\omega t) + \mathbf{e}_y\cos(\omega t + \delta)\right]$$

$$V_{\mathrm{ad}}(\mathbf{r}) = m_F g_F \mu_B \sqrt{\Omega^2(\mathbf{r}) + \triangle^2(\mathbf{r})}$$

tuning the relative RF phase δ



$$\Omega(\mathbf{r}) = |\mathbf{B}_S(\mathbf{r})| - \frac{\hbar\omega}{|g_F\mu_B|}$$

$$\triangle(\mathbf{r}) = \frac{B_{RF}}{2}\left[1 + \frac{B_I \sin\delta_{eff}}{|\mathbf{B}_S(\mathbf{r})|} + \frac{G^2\rho^2}{2\,|\mathbf{B}_S(\mathbf{r})|^2}\left(\cos\delta_{eff}\sin(2\phi) - 1\right)\right]$$

state dependent

$$\boxed{\delta_{eff} = \frac{g_F}{|g_F|}\delta}$$

I. Lesanovsky et al.PRA **73**, 033619 (2006) e-print archive: physics/0510076

RF and MW induced state dependent potentials

$|F=2, m_F=1\rangle$

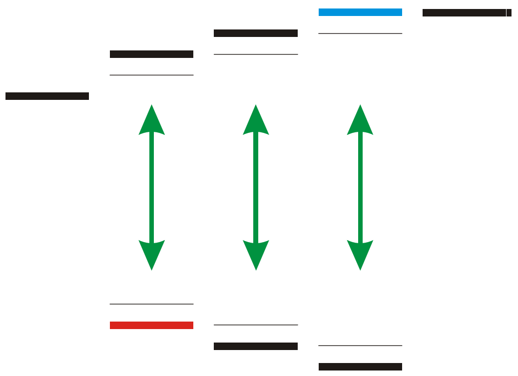
$|F=1, m_F=-1\rangle$

The two clock states have
- Identical Zeeman shift
- Identical Stark shift
- Identical light shift (for large detuning)

Radio Frequency (RF) and Micro Wave (MW) fields can couple differently

On chip: local RF and MW field for manipulaion

Linear polarized micro wave

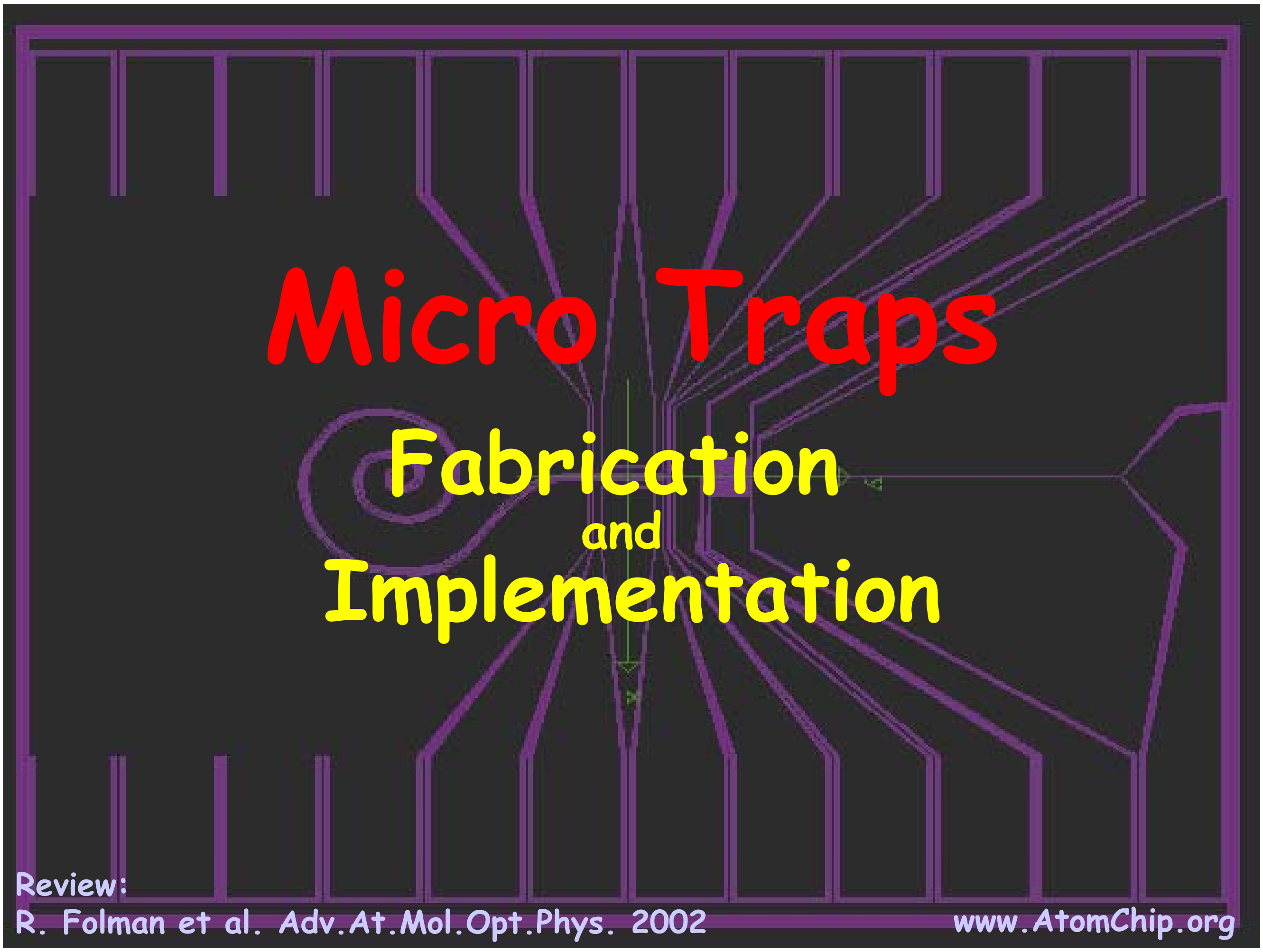


AC-Zeeman shift:

$$\Delta E = \pm\frac{\hbar\Omega_R^2}{4\Delta}, \quad \text{with} \ \ (|\Delta| >> \Omega_R)$$

$$\hbar\Omega_R \sim \mu_B \cdot B_{MW}$$

M. Cirone et al. quant-ph/0505194 (EPJ D special issue atom chip)
RF idea: M. Anderson (HD)



Micro Traps

Fabrication and Implementation

Review:
R. Folman et al. Adv.At.Mol.Opt.Phys. 2002

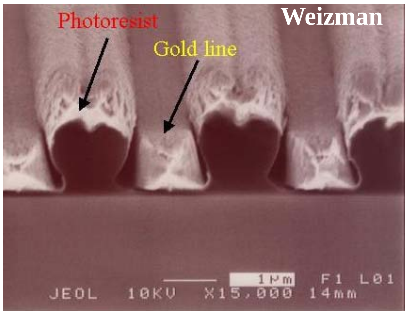
www.AtomChip.org

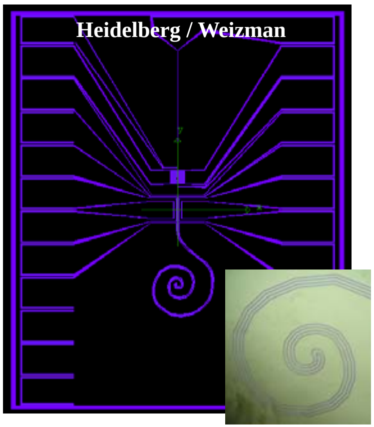
ATOM CHIP
fabrication of microscopic atom traps

Adapted nanofabrication technique to needs of Atom Chip (Weizman, Innsbruck/Heidelberg, TU-Vienna)

Features:

- Chip = mirror ⟶ wires are defined by etchings
- structures down to 1 µm
- current densities $> 3\ 10^7$ A/cm^2
- high voltages > 500V
- trap frequencies > 1MHz
  ground state size ~10 nm
- multi layer possible

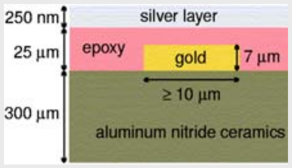


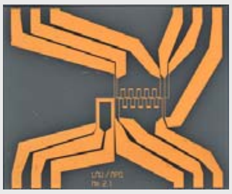


Other techniques (MPQ, Orsay):

Thin film hybrid technology

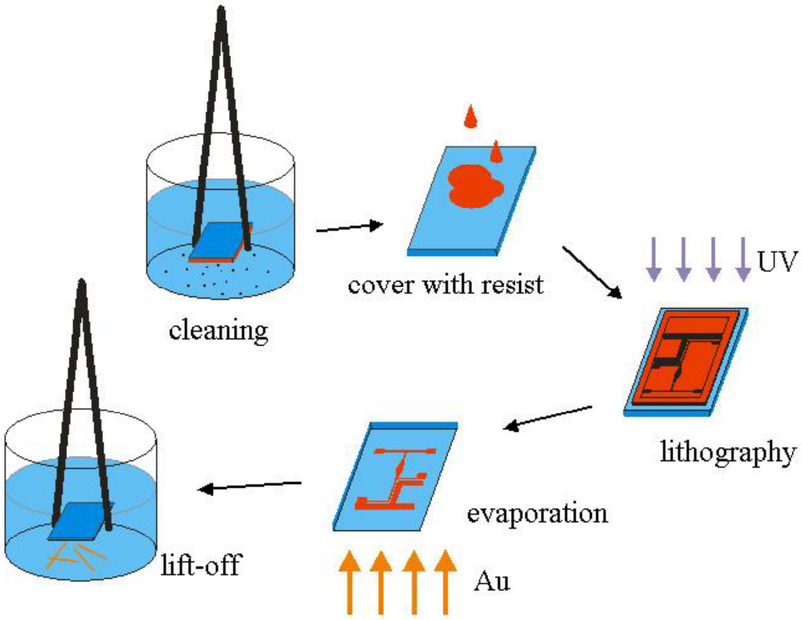
- Larger structures
- Large cross section
- High currents

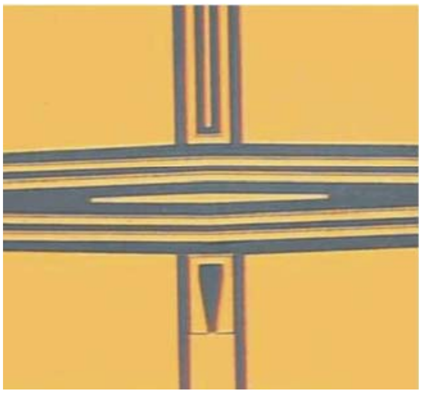


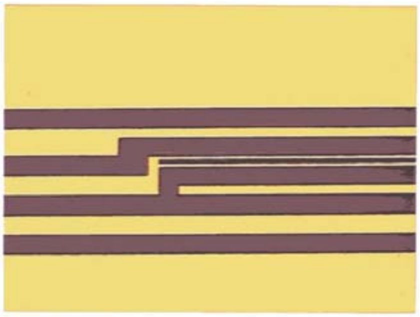


Atom Chip Fabrication

WIS - HD



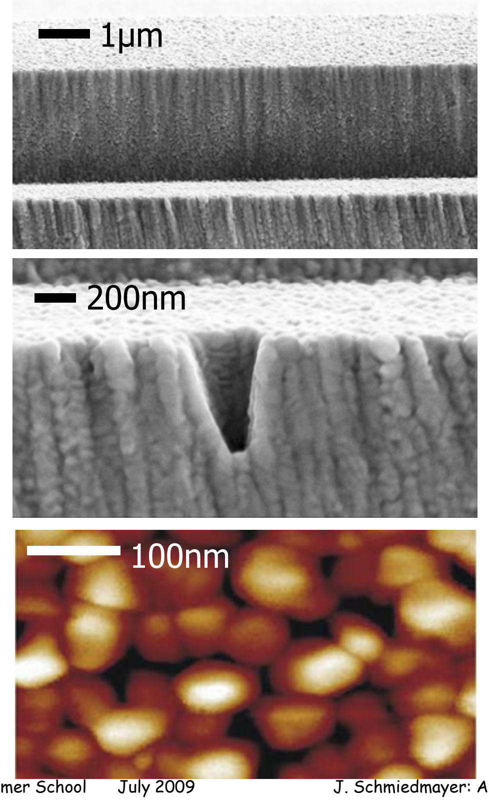




Adapted from standard semiconductor nanofab.
Innsbruck, Heidelberg, Weizmann, ATI

S. Groth et al. Appl. Phys. Lett. **85**, 2980 (2004)

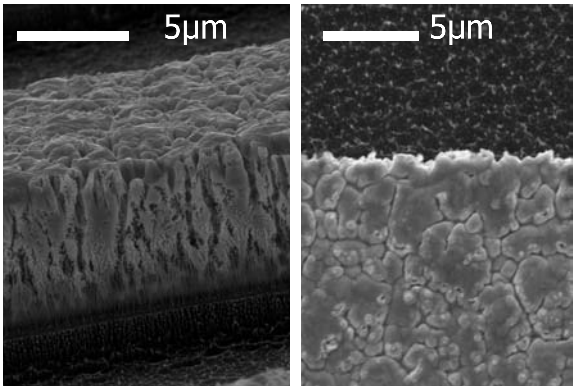
Chip surfaces



lithographically pattered atom chips
Innsbruck-Heidelberg-Weizman

electroplated chips (Orsay)

Estève et al., cond-mat 2004



Atom Chip

Fabrication

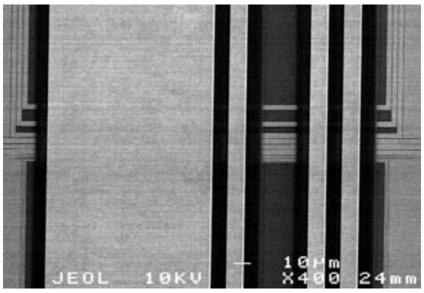
Adapted from standard semiconductor nanofab.
Innsbruck, Heidelberg, Weizmann, TU-Wien

Multi layer structures for sub µm manipulation of atoms.

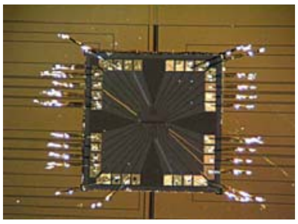
- J_{max} up to 10^8 A/cm^2
- RF and MW near fields
- Electric potentials ~100V
- Optical potentials (high quality mirror)
- etc ...

AtomChip with direct write e-beam lithography

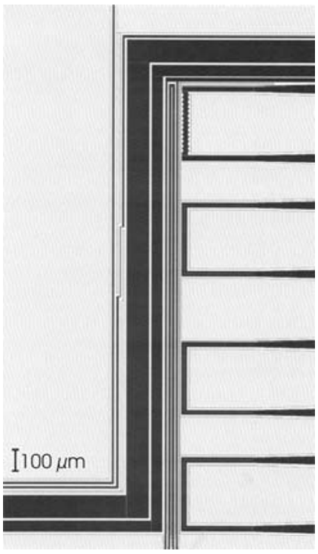
2 layer Au on Si AtomChip for QIPC



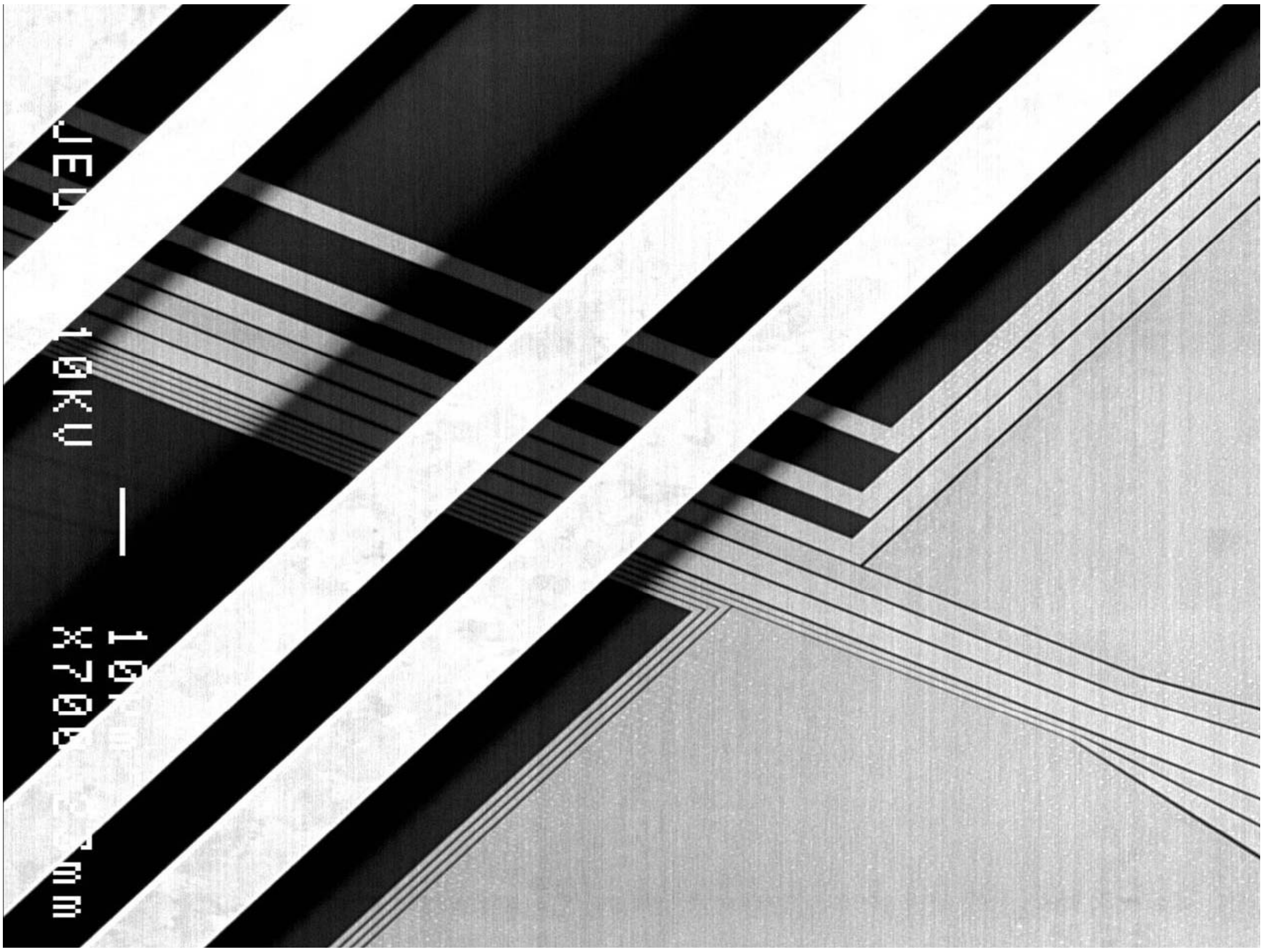
AtomChip in GaAs quantum wells

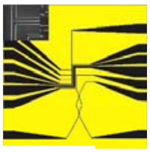


Layout of AtomChip used in the experiments



S. Groth, et al, Appl. Phys. Lett 85, 2980 (2004)





Heating of the Wire
a simple model

Model the heat transfer to the substrate:

- Contact resistance (fast time scale)
- Heat conductivity into the sample (slow time scale)
- Finite thickness of sample

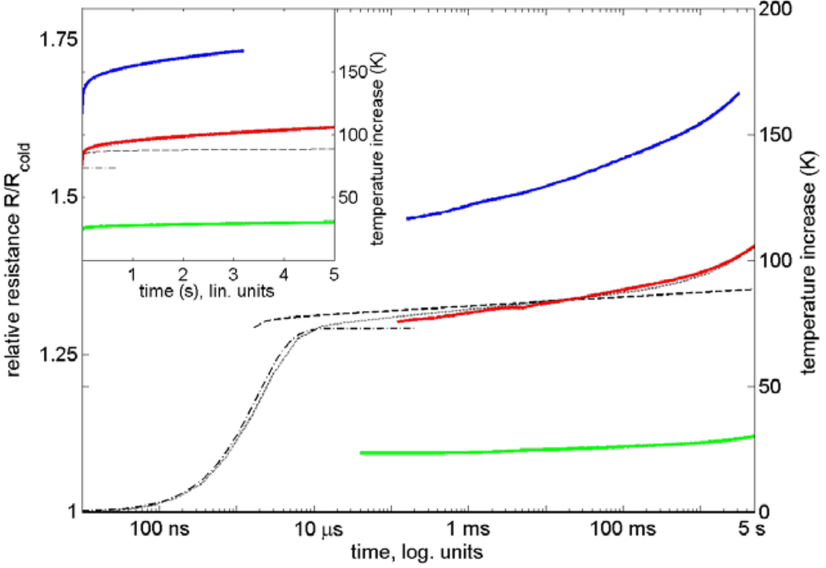
Important:

- Heat capacity
- Heat conductivity

For us the choice:

- Si
- GaAs

S. Groth et al. Appl. Phys. Lett. **85**, 2980 (2004)



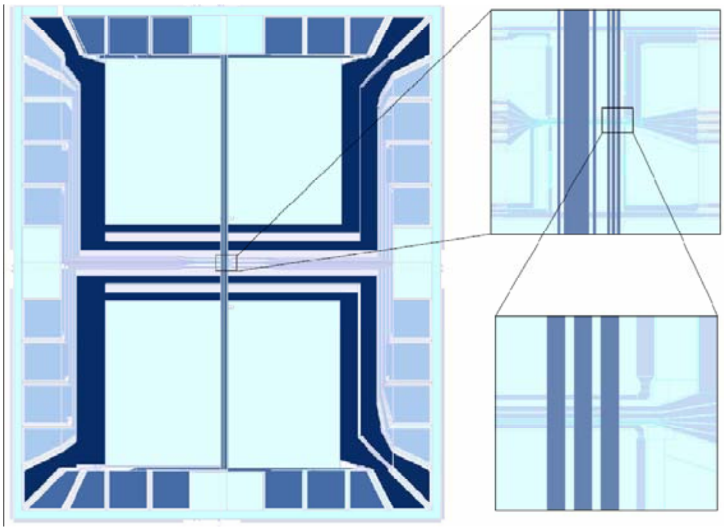
Fast rise of the temperature due to the finite thermal contact resistance between the wire and the substrate limits the current density one can send through the wires.

Thin wires: $j_{max}>10^8$ is possible

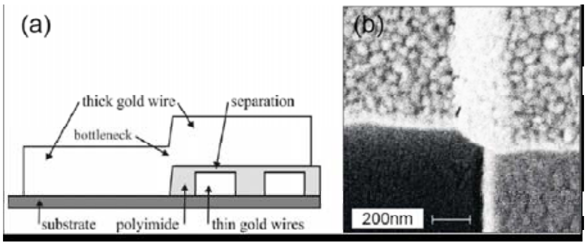
Multi Layer Chips

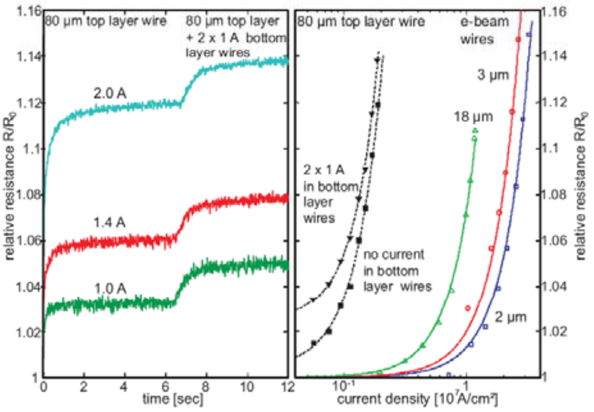
M. Trinker et al. Appl. Phys. Lett. **92**, 254102 (2008)

combine conventional lithography
with direct write e-beam lithography
for nano structures



thin insulation layer separates
small from large structures

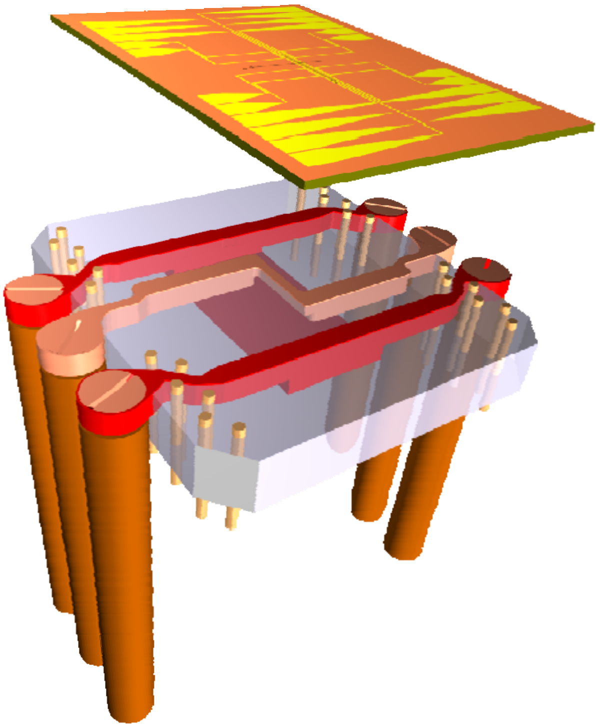




Experimental Setup

Micro fabricated AtomChip

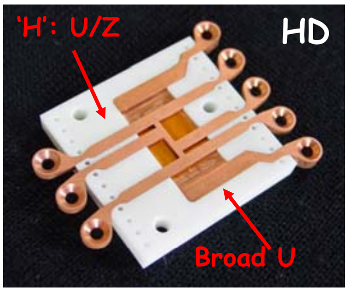
mini structure to load and cool atoms

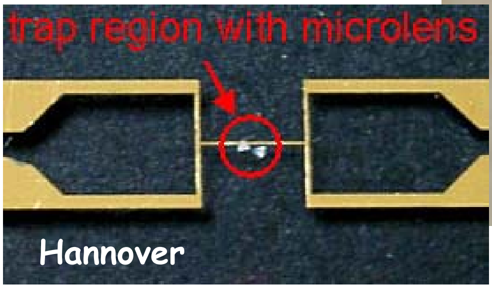


ATOM CHIP
implementation

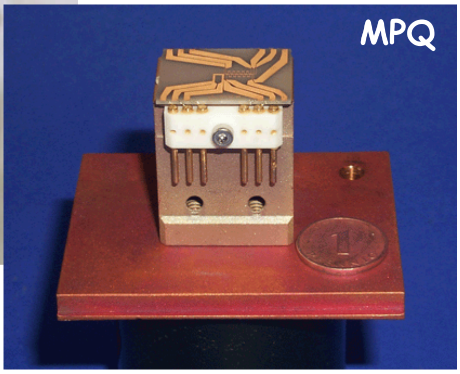
nano fabricated chip compatible with $p<10^{-11}$ torr

Support structure underneath the chip





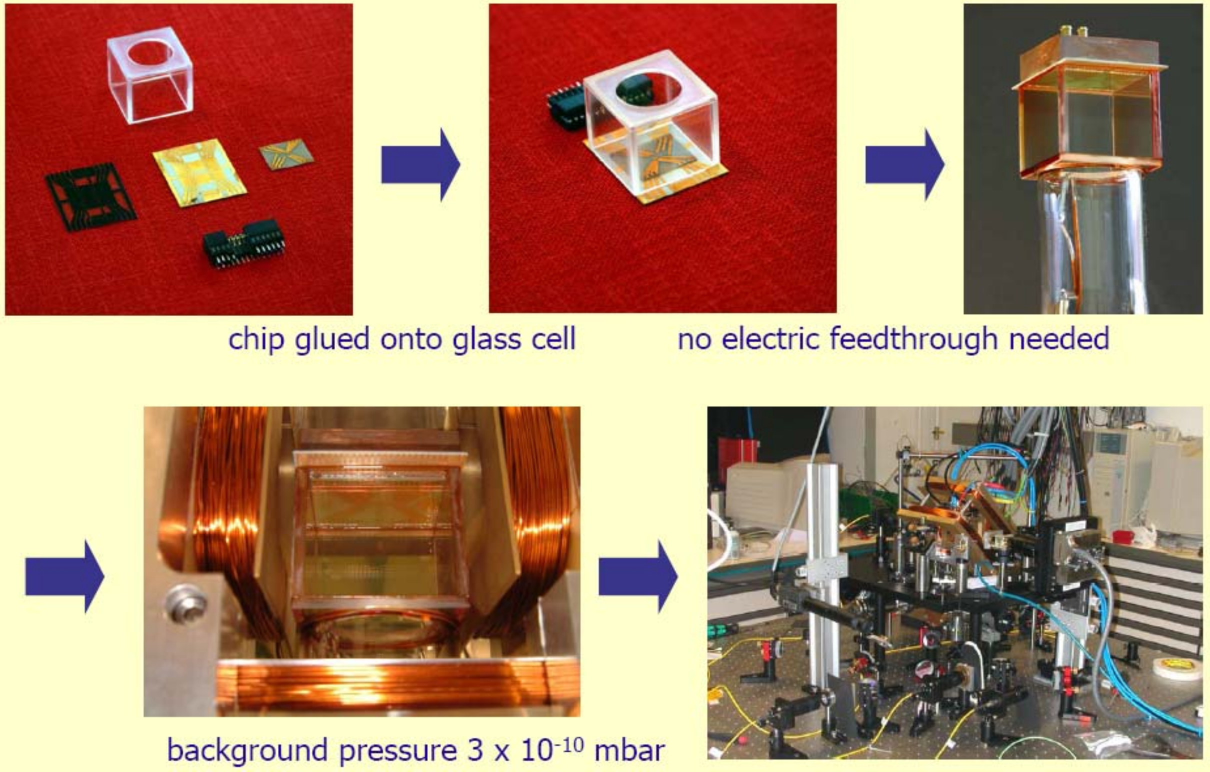
Chip with integrated lens



thin film hybrid technology

Simple Atom Chip Set-up

MPQ



chip glued onto glass cell

no electric feedthrough needed

background pressure 3×10^{-10} mbar