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13. ABSTRACT (Maximum 200 words)

The Quantum Information in Group IV Semiconductors workshop provided the first opportunity for an intensive meeting of the specialists working on electron spin qubits in semiconductors, that have emerged as a major candidate qubit system, owing to the long spin decoherence lifetimes.

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Final Report on the Quantum Information in Group IV Semiconductors Workshop
March 28-29, 2003

There was much new information on the behavior of spins in the group IV semiconductors, Silicon, Germanium, and Diamond. While this material system has gigantic advantages for quantum information processors there are still unanswered questions:

1. Does the strong hyperfine dephasing in the group III-V semiconductors rule them out, or is there some work-around possible.
2. Is nearest neighbor quantum communication adequate, or will it place too large an error threshold burden on the quantum error correction algorithm?

More specific description of the activities of the workshop are in the record appended here:

Day 1, Group A

Questions
(1, 2, 3, 6 were discussed in Group A)

1. What are the critical experiments that need to be done soon (<3-5 years) to convince people funding us that we are on the right track?

2. What is the potential performance of the various qubit options in Silicon, electron spin, P31, Si29, etc.

3. Has anybody been able to measure a single spin STATE in condensed matter yet? Why has nobody been able to measure Rabi oscillations from a single spin STATE in condensed matter yet? Is it important for this type of measurement to be made by a transistor-like device?

4. What are the possible forms of electric charge sensors, SET, FET, etc. Do they all perform about equally well?

5. What are all the possible available spin/charge conversion mechanisms? Does any one of those mechanisms have an advantage? Is optical readout a reasonable alternative option for spin readout?

6. What type of theoretical work needs to be done, particularly for the development of specific scaleable QC architectures, so that all the relevant engineering issues confronting large scale QC can begin to be addressed?

Discussion

Break-Out session Friday afternoon, Mar. 28.

The questions were:

What is the potential performance of the various spin qubit options:
electron spin in Silicon, P31, Si29, or GaAs?

1. There was a belief that there was a distinction between long term requirements for the program, and short term requirements.

1(a). Near-term mileposts can be met by a slightly different technology, than what would ultimately be used in the long term. At the same time, it is important to continue to support long term approaches.
1(b). Long-term approaches have more difficult fabrication problems, but they do present good benefits that will ultimately be essential.

Examples of near term approaches are e-qubits in GaAs, while the group IV qubits may take longer to develop, they do have better decoherence in the long run.

Has anybody been able to measure a single spin STATE in condensed matter yet? Why has nobody been able to measure Rabi oscillations from a single spin STATE in condensed matter yet?

2. Milestones to look forward to:
2(a). Single spin state measurement, must be done within T1.
2(b). Rabi oscillations, or Free-Induction decay, must be done within T2.
Alternately there are the corresponding double-qubit operations that can act as mile-posts:
2(c). Distinguish between a single engineered Singlet & engineered Triplet, within the lifetime of those states.
2(d). Perform a swap operation, and prove it by measurement within T2.

3. Progress toward mile-stones:
3(a). A single e-spin, and a single C13 spin state have already been measured by Wrachtrup. Wrachtrup did pi pulses, and says he could have easily generalized this to the observation of Rabi oscillations. Therefore mile-post 2(a) & 2(b) may have already been met.
3(b). Kouwenhoven claimed that he was only weeks away from a single spin state measurement in GaAs quantum dots, that would satisfy milepost
2(a). (Up until now he had only done ensemble type measurements.)
Kouwenhoven says that he would have a SWAP operation by the end of the year, satisfying milepost 2(d).

Is it important that this type of measurement to be made by a transistor-like device?

4. Purely electrical spin measurement is not essential. Optical measurement (as by Wrachtrup) is fully acceptable, and may actually be beneficial in the context of Quantum communication.

5. The issue of Spectral Diffusion was also addressed:
5(a). Das Sarma said that Spectral Diffusion was implicitly included in the effective decoherence, that led to the observed 1/e T2 time.
5(b). Yablonovitch said that Spectral Diffusion was more serious since the need for frequent re-calibration of the qubit frequency had prohibitive effects on the quantum processor architecture.
5(c). Daniel Loss said that 80% nuclear spin orientation suppresses nuclear spin induced decoherence, but that the same effect would occur for electrons in Si at a finite magnetic field. The discussions between Loss & Yablonovitch are continuing, with the next step being the exchange of pre-prints.

<u>Day 1, Group B</u>

<u>Questions</u>
(1, 4, 5, 6 were discussed in Group B)

1. What are the critical experiments that need to be done soon (<3-5 years) to convince people funding us that we are on the right track?

2. What is the potential performance of the various qubit options in Silicon, electron spin, P31, Si29, etc.

3. Has anybody been able to measure a single spin STATE in condensed matter yet? Why has nobody been able to measure Rabi oscillations from a single spin STATE in condensed matter yet? Is it important for this type of measurement to be made by a transistor-like device?

4. What are the possible forms of electric charge sensors, SET, FET, etc. Do they all perform about equally well?

5. What are all the possible available spin/charge conversion mechanisms? Does any one of those mechanisms have an advantage? Is optical readout a reasonable alternative option for spin readout?

6. What type of theoretical work needs to be done, particularly for the development of specific scaleable QC architectures, so that all the relevant engineering issues confronting large scale QC can begin to be addressed?

<u>Discussion</u>
"It would be great if someone . . ."

1. Detected a single electron spin
2. Detected a single nuclear spin
3. Saw Rabi oscillations in a single spin
4. Saw local singlet-triplet splitting
5. Demonstrated (coherent) controlled single electron transfer adiabatically from single donors A-B-A
6. Did spectroscopy on a spin system
7. Measured spin relaxation processes, T1, and T2, in 2D, 1D, and 0D Si and SiGe, etc.
    a. Emphasize early time effects
    b. Specify spin Hamiltonian thoroughly
8. Integrated measurement device with spin Qbit
    a. Similar to what was done in superconductors
9. Demonstrated an optical readout technique addressably applied to Si or other semiconductors
    a. Use local control (gates) for addressing

1. Used optical techniques and gates to address arrays of spins
2. Made a spin filter in Si
3. Measured the efficiency of the Si spin filter
4. Compared SQUID vs Hall bar techniques
5. Compared SET vs FET techniques
    a. Appear to have little differences/advantages
6. Looked at alternatives: QPC, cantilevers?
    a. Clever ways to measure that depend on the system or material rather than simply on the technique
7. Performed a detailed investigation of spin relaxation in real SiGe systems, including the effects of confinement, surfaces, and interface effects
    a. Phenomenological, not first principles
8. Looked at how spin is conserved through excitation and transport, leading to a detailed understanding of spin dynamics in Si band structure
9. Are there fundamental limits in the performance of the various measurement techniques? Where are we relative to those limits?
10. How does relaxation depend on degree and amount of entanglement?
11. Are there error resistant or tolerant ways of implementing a Qbit?

Keith Miller’s additional comments and notes

I took some discussion notes in room B on both days; on the second day, it looks like the room A topics were in room B. Other people did the condensing into questions, but I do have a few comments that perhapsshould be included somehow, probably without the names attached.

Friday:

Sturm: There has been amazing progress in commercial disk read-write heads, which should be followed.

Marcus: Commercial AFM read heads are comparable to scan probes.
Katherine Moller (?) at Stanford is a good source for information.

Schoelkopf: Charge measurement in a semiconductor can't be discussed separately from a whole architecture for spin -> charge conversion.

Marcus: There's an important result from Fujisawa about differential spin tunneling.

Marcus (agreed to by all): An important goal is developing a Si QD as quiet as GaAs QDs.

Awschalom: There is no Si infrastructure or funding, and few university people, in the US. [Is this really true?]

Kane: Edges and interfaces give serious problems which have to be measured, but there is still much to learn from bulk resonance measurements.

Kane, Marcus, Schoelkopf: FETs and SETs aren't wildly different for single-charge measurements. Theory and experiment agree on this.

Day 2, Group A

Questions
(7, 8, 9 were discussed in Group B)

7. If everything goes as planned, will it matter? What is the potential performance? Will it be so attractive, as to be more desirable than any other quantum computation option?

8. Is there any way to avoid characterizing each and every device separately, to make it usable in a system? Will the excessive sensitivity of the exchange interaction to device parameters cause problems in engineering a system?

9. What is the best on-chip quantum communication option; exchange transport, direct electron motion, exchange/teleportation, or Raman optical coupling?

10. For the case of electron spin qubits, does it matter whether the electron is trapped at a donor ion, by sodium ions in SiO2, or by electrostatic gates?

11. What are the critical materials issues that we need to address that will be necessary for scaleable device technology? Will the required Si/Ge heterojunction material quality actually be available? What are the real materials mile-posts? Will the required isotropic purity be available?

Discussion: Room A Session on Saturday:

TOPIC A: Is there any way to avoid characterizing each and every device separately, to make it usable in a system? Will the excessive sensitivity of the exchange interaction to device parameters cause problems in engineering a system?

Variability in solid state devices are a very significant problem the community must address. Sources include:

1. Fabrication variability
2. Alloy disorder (for Ge rich approaches)
3. Nuclear spins
4. Irregularities at interfaces

Calibration methods are possible in principle and quantum gates may be designed that tolerate variability, but these solutions are likely to introduce a substantial overhead to quantum computer operation.

The group noted that there are solid state systems (like Si:P) that are essentially atomically identical and that quantum computing with such systems may be possible. There was a strong suggestion that in the long term, atomic assembly and "bottom up" approaches to fabrication need to be explored so that maybe "solid state device variability" will become an obsolete criticism (much the way the 'unreliable' criticism of semiconductors became obsolete in the '60s).

TOPIC B: What is the best on-chip quantum communications option? exchange transport, direct electron motion, exchange/teleportation, or Raman optical coupling? Is there an architecture compatible with the preferred internal communication option?

The group was impressed with Daniel Gottesman's ideas on teleportation, but agreed that the issues of teleportation overhead needs to be addressed in the solid state context (how fast do measurements have to be? Under what circumstances will classical communication be easier than quantum communication?) We need to understand the situations where teleportation is superior to direct spin transport or swapping.

There was a consensus that quantum information transport via moving electrons seems to be the most promising on-chip approach, but photons have distinct advantages over longer distances.

It would be great if:

1. It would be possible to make atomically precise nanodevices (and thus circumvent solid state device variability)

2. It would be possible to do quantum information processing that is tolerant of static variability (i.e. if a theorist could show a way for doing QIP in a way that solid state device variability does not introduce a substantial overhead.)

3. An experiment is performed in the next few years in which it is shown that a spin can be transported coherently by moving a single electron.

Keith Miller's additional comments/notes

I took some discussion notes in room B on both days; on the second day, it looks like the room A topics were in room B. Other people did the condensing into questions, but I do have a few comments that perhaps should be included somehow, probably without the names attached.

Saturday:

Kane: Individual device characterization is probably necessary, since the alternatives are worse.

Yablonovitch and Schwab: No macroscopic qubits will be identical enough unless they're built to be atomically identical.

General conclusions: We *really* understand silicon. Nuclear spins will flip and change calibrations if there are any uncontrolled nuclear spins.

I think Bruce's notes accurately captured the sense of the discussion.

Day 2, Group B

Questions
(7, 10, 11 were discussed in Group B)

7. If everything goes as planned, will it matter? What is the potential performance? Will it be so attractive, as to be more desirable than any other quantum computation option?

8. Is there any way to avoid characterizing each and every device separately, to make it usable in a system? Will the excessive sensitivity of the exchange interaction to device parameters cause problems in engineering a system?

9. What is the best on-chip quantum communication option; exchange transport, direct electron motion, exchange/teleportation, or Raman optical coupling?

10. For the case of electron spin qubits, does it matter whether the electron is trapped at a donor ion, by sodium ions in SiO2, or by electrostatic gates?

11. What are the critical materials issues that we need to address that will be necessary for scaleable device technology? Will the required Si/Ge heterojunction material quality actually be available? What are the real materials mile-posts? Will the required isotropic purity be available?

Discussion
"It would be great if someone . . ."

1. Provided good quality (>10^4 Ohm-cm) intrinsic Si.
2. Provided good, low interface trap density oxides (<10^8 cm^{-2}) with low fixed charge density (<10^{10} cm^{-2})
   a. Trap density due to Si dangling bonds
   b. Fixed charge density due to impurities
      i. Make a MOSFET or other CMOS device and measure mobility
      ii. Solution existed in USSR > 10 years ago
3. Had a way to gate charges reliably and insensitively to these stray charges
   a. Problem in SiGe: Si cap grown @ low temperature
      i. Leads to oxide and charge problems
4. Had a way to make gates with or without SiO_2
   a. Schottky-like structures possible?
      i. Too leaky, want leakage < 1 nA @ 1V, want low charge density @ QD
5. Bought us a bunch of 99.999% ^{28}Si ingots or silane grown into an epilayer
6. Grew good, low dislocation density buffer layers of SiGe (<10^4 cm^{-2})
7. Studied charge traps with RF-SETs
8. Evaluated possible molecular hosts
9. Made Si and Ge QDs as "quiet" as GaAs QDs
   a. Stable over long times

    a. Low 1/f noise (in any Si device, not just QDs)
2. Demonstrated wafer bonding as an alternate to Si overgrowth
3. Developed a center with all (most?) the tools in one place in the US (as in Australia)
    a. We need a national center, a mini- "Manhattan Project" with industry
        i. Atomic level processors (FIB etc.)
        ii. Normal micropositioning (gates etc.)
        iii. State of the art and new types of characterization (LT-STM etc.)
4. Developed gated GaAs QD systems first
    a. Goal: demonstrate all the elements we hope to see in P-doped Si
5. Placed a single donor with atomic precision in a host, then in a device
6. Precisely placed two donors with atomic precision
    a. Then perform singlet-triplet measurements
7. Proved the implantation technique using other atoms first, then moved to P
    a. Make simple devices just to prove you can make them
8. Found a donor with a larger wavefunction extent
    a. Decreases entanglement with nuclear spin
9. Figured out how many atoms could be in a cluster and yet retained atom-like Qbit properties
10. Designed a large scale architecture based on gated QDs (ala Kouwenhoven)
11. Looked at GaAs lessons learned regarding alloy problems
    a. Want pure Si in QWs
    b. Digital alloys?

22987 /R1/JS

FINANCIAL STATUS REPORT

(Follow instructions on the back)

1. FEDERAL AGENCY AND ORGANIZATIONAL ELEMENT TO WHICH REPORT IS SUBMITTED U.S. ARMY RESEARCH, WASHINGTON D.C. OFFICE	2. FEDERAL GRANT OR OTHER IDENTIFYING NUMBER DAAD19-03-1-0047 OMB Approved No. 80-R0180
3. RECIPIENT ORGANIZATION (Name and complete address, including ZIP code) THE REGENTS OF THE UNIVERSITY OF CALIFORNIA UNIVERSITY OF CALIFORNIA, LOS ANGELES 10920 Wilshire Blvd., 5th Floor, Suite 500 LOS ANGELES, CA 90024-6502	4. EMPLOYER INDENTIFICATION NUMBER 95-6006143 5. RECIPIENT ACCOUNT NUMBER OR IDENTIFYING NO. 22987 6. FINAL REPORT [X] Yes [ ] No 7. BASIS [ ] Cash [X] Accrual

8. PROJECT PERIOD (see instructions) FROM (Month, day, year)	TO (Month, day, year)	9. PERIOD COVERED BY THIS REPORT FROM (Month, day, year)	TO (Month, day, year)
03/26/2003	03/25/2004	03/26/2003	03/25/2004

10. STATUS OF FUNDS

a. Net outlays previously reported	$ -
b. Total outlays this report period	23,918.00
c. Less: Program income credits	0.00
d. Net outlays this report period (Line b minus line c)	23,918.00
e. Net outlays to date (Line a plus line d)	23,918.00
f. Less: Non-Federal share of outlays	0.00
g. Total Federal share of outlays (Line e minus line f)	23,918.00
h. Total unliquidated obligations	0.00
i. Less: Non-Federal share of unliquidated obligations shown in line h	0.00
j. Federal share of unliquidated obligations (Line h minus line i)	0.00
k. Total Federal share of outlays and unliquidated obligations (Line g plus line j)	23,918.00
l. Total cumulative amount of Federal funds authorized	23,918.00
m. Unobligated balance of Federal funds (Line l minus line k)	$ -

11. INDIRECT EXPENSE	a. TYPE OF RATE (Place "X" in appropriate box)	[ ] PROVISIONAL [X] PREDETERMINED	[ ] FINAL [ ] FIXED
b. RATE	c. BASE $.00	d. TOTAL AMOUNT $.00	e. FEDERAL SHARE $.00

12. REMARKS : (Attach any explanations deemed necessary or information required by Federal sponsoring agency in compliance with governing legislation.)

13. CERTIFICATION	SIGNATURE OF AUTHORIZED CERTIFYING OFFICIAL	DATE REPORT SUBMITTED
I certify to the best of my knowledge and belief that this report is correct and complete and that all outlays and unliquidated obligations are for purposes set forth in the award documents.	Rachel Aglesias (signature) for	09/02/2004
	TYPED OR PRINTED NAME OR TITLE Evelyn Balabis, Director Extramural Fund Management	TELEPHONE (Area code, number and extension) (310)794-0227

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