High-speed switching of spin polarization for proposed spin-photon memory

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Nonvolatile high-speed optical memory is proposed, which utilizes the magnetization reversal of nanomagnet by spin-polarized photoexcited electrons. It was demonstrated experimentally that one selected pulse from the train of two optical data pulses with interval of 450 fs can solely excite the spin-polarized electrons without a disturbance from the unselected optical data pulse. That proves feasibility for operation of the memory with speed of 2.2 Tbits/s. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3106637]

Data processing and transmission need faster operational speed. The record transfer rate of 25.4 Tbits/s through single optical fiber was demonstrated.[1] However, due to the speed limitation of present electronic components, the data was transferred using many channels at different optical frequencies. Since each channel needs individual electrical and electro-optical components, such system is complex and expensive. With availability of higher speed data processing components, the high broadband of optical fiber can be used in wider range of applications. All-optical data processing can significantly increase the operational speed.[2–5] However, in the case of the conventional all-optical data processing, which utilizes the nonlinearity of optical amplifier, the speed is limited by gain and refractive index recovery time, which is about 2–100 ps.[4,5] For the faster devices, the short recovery time of nonlinear optical refraction of glass fiber can be used. However, since the nonlinearity of glass is small ($\sim 3 \times 10^{-10}$ m^2 W^{-1}), for the operation of such devices the length of fiber of several kilometers and high optical power are needed.[4] In this paper we are proposing the nonvolatile optical memory, for which the recording speed is not limited by the gain recovery time. In the proposed design the data are recorded by the photoexcited electrons of one spin direction. Below we will show that the spin direction of the photoexcited electrons can be switched with the speed of 2.2 Tbits/s, and this switching has negligibly small relaxation time. Therefore, the proposed memory may operate with speed of several Tbits/s. If realized, it will advance data processing and computing technology toward faster operation speed.

Figure 1 shows the proposed design. The memory consists of microsized memory cells integrated on a semiconductor wafer. A bit of data is stored by each cell. Each cell consists of semiconductor-made photo detector and nanomagnet made of a ferromagnetic metal. The nanomagnet has two stable magnetization directions. The data is stored as a magnetized direction in the nanomagnet. For the data reading, the dependence of optical loss in waveguide on magnetization direction can be used.[6,7] For the data recording, the magnetization direction must be reversed by optical pulse. The circularly polarized optical pulse is absorbed in the semiconductor detector creating spin-polarized electrons. Under applied voltage these spin-polarized electrons are injected from the detector into the nanomagnet. The spin transfer torque is a consequence of the transfer of spin angular momentum from a spin-polarized current to the magnetic moment of a nanomagent.[8,9] If the torque is sufficient, the magnetization turns and the data is memorized. Due to the optical selection rule, the spin-polarized electrons can be created only by the circularly polarized optical pulse. The linearly polarized light excites equal amount of electrons of both up and down spins, therefore there is no net spin polarization. The current injected into the nanomagnet is not spin-polarized and there is no spin torque.

Figure 2 shows integration of two memory cells and explains the principle of high-speed recording. There are two waveguide inputs. One input is for data pulses and one input is for the clock pulse. The clock pulse is used to select for recording a single pulse from the sequence of the data pulses. Polarization of data pulses and clock pulse are linear and mutually orthogonal. Optical paths were split that each memory cell is illuminated by the data pulses and the clock pulse. The lengths of waveguides are adjusted so that the phase difference between clock and data pulses is $\lambda/4$ at each memory cell. At the first memory cell the clock pulse came at the same time with first data pulse. Therefore, these two pulses combined into one circularly polarized pulse. Since only the first pulse is circularly polarized, only this pulse excites spin-polarized electrons, changes magnetiza-

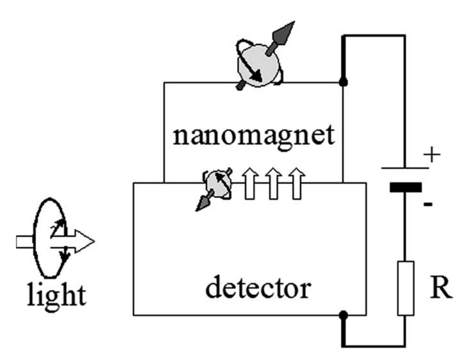

FIG. 1. Design of spin-photon memory cell. A bit of data is stored as magnetized direction of nanomagnet. For the data recoding, the circularly polarized light creates spin-polarized electrons in the detector. Injection of these electrons into the nanomagnet causes magnetic torque, which turns the magnetization of nanomagnet, and the data is memorized.

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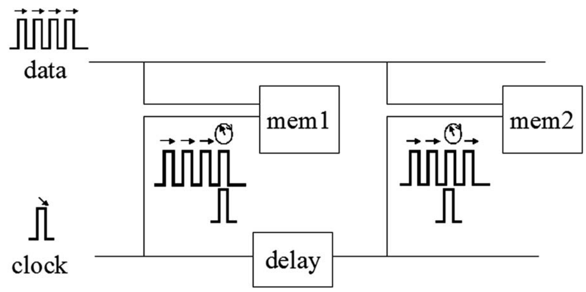

FIG. 2. The scheme for the integration of memory cells. Pulse diagrams explain the method for the high-speed recording.

tion, and is memorized. All other data pulses are linearly polarized. They do not excite spin-polarized electrons and they have no effect on the magnetization. For the second memory cell, the clock pulse is slightly delayed relatively to the data pulses and it comes together with the second data pulse. Only the second pulse is circularly polarized and can be memorized by the second memory cell. Therefore, each data pulse can be memorized by individual memory cell. The closer the pulses can be placed relatively to each other, the more data can be transformed through one line and the faster recording speed of memory can be achieved. The minimum interval between pulses, at which a pulse can be recorded without any influence of nearest pulse, determines the recording speed of the memory.

Heberle *et al.*[10] showed that spin-polarized excitons can be excited by two linearly cross-polarized pulses even when the pulses arrived at different times. If the exciton dephasing time is longer than the interval between pulses, the excitons excited by two pulses can coherently interfere[10,11] and create spin polarization.

For the demultiplexing by the method proposed in Fig. 2, the interval between data pulses should be at least longer than the electron dephasing time. Also, the spin polarization created by circularly polarized pulse should not be destroyed by following linearly polarized pulses. Next, we verified the proposed demultiplexing method at the speed of 2.2 Tbits/s. For this purpose, we studied the dynamics of excitation of spin-polarized electrons in Si-doped GaAs ($n=7\times10^{16}$ cm^{-3}) at 80 K.

Figure 3 shows the experimental setup. A mode-locked Ti:sapphire laser ($\lambda=820$ nm) provides 160 fs linearly polarized pump and probe pulses. Polarization of the pump was rotated by a $\lambda/2$ waveplate and split by polarization beam splitter (PBS) into clock pulse and data pulse of linear and mutually orthogonal polarizations. The data pulse was split into two pulses. The second data pulse was $165\lambda(\sim450$ fs) delayed. Clock and data pulses were combined together by another PBS and focused on the sample. The linearly polarized probe beam was 100 ps delayed relatively to the pump and focused on the same spot on the sample. The spin polarization of electrons excited by pump beam was estimated from Kerr rotation angle of the probe beam.[12–15] The rotation angle of reflected probe beam was measured by polarizer (P) and photodetector (det). Intensity of each data pulse was $1-10$ $\mu\text{J/cm}^2$. Intensity of the probe pulse was ten times smaller. The data pulses and clock pulse were phase-locked. When the clock pulse and one of the data pulse nearly coincided, the positive and negative angles of Kerr rotation were observed for delays of $(n+1/4)\lambda$ and $(n-1/4)\lambda$, respectively. When the pulses were away from each other, the Kerr rotation was not observed.

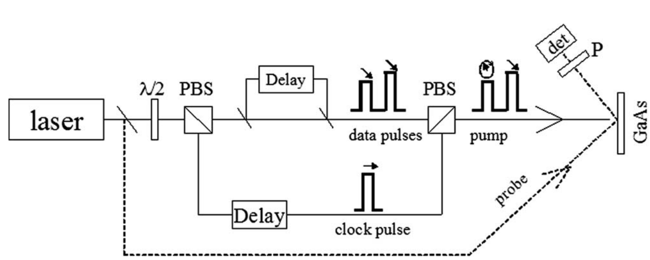

FIG. 3. Experimental setup for the study of the recording speed for spin-photon memory.

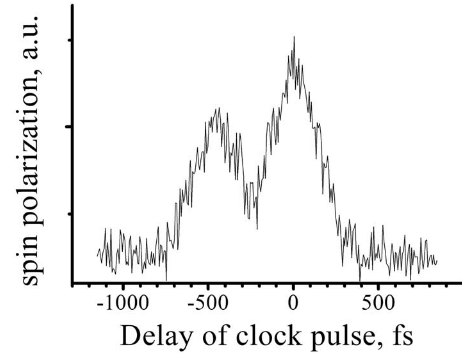

FIG. 4. Spin polarization of electrons excited by combined beam of clock pulse and two data pulses as a function of delay of clock pulse. For each point, the delay length was $(n+1/4)\lambda$, where n is an integer. Reading of spin polarization was done 100 ps after arrival of pump pulses.

Figure 4 shows spin polarization of the excited electrons as a function of delay between clock pulse and first data pulse. For each point the delay length was equal to $(n+1/4)\lambda$, where n is an integer. The maximum of spin polarization was observed when the clock pulse coincides with the first data pulse. The spin polarization decreases when the clock pulse is delayed out of the first data pulse, and again increases as the clock pulse coincides with the second data pulse. Figure 4 clearly shows that the spin polarization excited by the second data pulse can be separately distinguishable from the spin polarization excited by the first data pulse. This means that from two closely placed optical data pulses, only one pulse can trigger the recording without influence from another pulse. The interval between the data pulses is 450 fs. It corresponds to the recording speed of 2.2 Tbits/s. Notice that the detection of spin polarization was done 100 ps after the data pulse arrived. This means that the lifetime of the spin-polarized electrons is sufficiently long to inject the spin-polarized electrons into the nanomagnet for the magnetization reversal.[16,17]

For the memory operating at the speed of 2.2 Tbits/s, the delay of clock pulse between cells (Fig. 1) should be $165\lambda(\sim450$ fs), the initial magnetization of all nanomagnets should be spun down and the delay of data pulses relatively to the clock pulse should be $(1/4+m\times165\times\lambda)$, where m is a number of the data pulse. As a result of Fig. 4, in this case in each cell, only one data pulse excites spin polarization and is memorized there. Other data pulses have no influence on spin polarization of that cell. In our experiment, the shortest interval between the data pulses, when the spin polarization excited by each pulse can be individually distinguished, is about 450 fs. For shorter interval the spin polarization is overlapped and the spin polarization created by preceding data pulse is reduced by next data pulse, which is causes overwriting of data of preceding pulse by next pulse in the cell. Therefore, the memory cannot operate at speed faster than 2.2 Tbits/s.

By these experiments we demonstrated that from sequence of short-interval pulses it is possible to select only a single pulse for excitation of spin-polarized electrons. That proves high recording speed of this memory. For the memory to be fully functional, the magnetization reversal by spin-polarized photoexcited electrons should be realized. It requires injection of sufficient amount of spin-polarized current from the detector into the nanomagnet.[8,9,16,17] Also, the time for the injection of the photocurrent from the detector into nanomagnet needs to be adjusted so that it should be long enough to accomplish the magnetization reversal of the nanomagnet, but still it should be shorter than the electron spin lifetime in the detector. The time which takes the magnetization of nanomagnet to turn between two stable direction is about 500–1000 ps.[16,17] There are several semiconductors, in which the electron spin lifetime is longer or comparable with that time. For example, the spin life time is 100 ns in GaAs at $T=4$ K (Ref. 12) and 100 ps at room temperature (RT),[14] 10 ns in GaAs/AlGaAs quantum well (QW) at RT (Ref. 15), and several nanoseconds in ZnSe QW at RT.[13] For the design in Fig. 1, the photocurrent injected in nanomagnet decays with time constant $\tau_{RC}=RC$, where C is capacity of detector and R is resistance of close loop. The τ_{RC} should be comparable with magnetization reversal time of the nanomagnet and smaller than the spin life time in the detector.

To estimate the energy of optical pulse required for magnetization reversal, we assumed that τ_{RC} is 500 ps, the efficiency of photon to spin conversion is 40%, and the critical current for the magnetization reversal is 5 mA.[16,17] To generate such current, the required energy of optical pulse should be about 3 pJ. It is in the range of the pulse energies which is typically used in case of all-optical switching.[2–5,18] Therefore, the memory may be suitable for the use in present optical communication systems.

In conclusion, the high-speed nonvolatile optical memory is proposed. The fast recording speed of this memory benefits from short electron dephasing time in semiconductors. The high-speed switching of spin polarization in GaAs was demonstrated. It was shown that one selected pulse from the train of two optical data pulses with interval of 450 fs can solely excite the spin-polarized electrons without a disturbance from the unselected optical data pulse. Since the memory is designed so that only spin-polarized electrons can be recorded, it proves feasibility for proposed memory to record the data train with rate of 2.2 Tbits/s. This memory is compact, integratable, compatible with present semiconductor technology, and it has fast operation speed. If realized, it will advance data processing and computing technology toward faster operation speed.

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