[0049] The synthetic nanoparticles described above can be produced in large quantities using a large wafer and standard vacuum thin film deposition processes. For example, with a 6-inch round wafer, we can produce 30-nm diameter nanoparticles at a rate of roughly 5×10^{12} particles per run, assuming each particle occupies a square of 60 nm by 60 nm on the wafer.

[0050] High Sensitivity Spin Valve Detectors

[0051] A spin valve detector is a metallic multilayer thin-film structure of two ferromagnetic layers spaced by a non-magnetic layer such as copper. One ferromagnetic layer, called the pinned layer, has its magnetization pinned to a certain direction, while the magnetization of the other ferromagnetic layer, called the free layer, can rotate freely under an applied magnetic field. The electrical resistance of a spin valve depends on the relative orientation of magnetization of the free layer to that of the pinned layer. When the two magnetizations are parallel, the resistance is the lowest; when antiparallel, the resistance is the highest. The relative change of resistance is called the magnetoresistance (MR) ratio. The MR ratio of a spin valve can reach more than 10% in a small magnetic field, e.g., 100 Oe. Therefore, a spin valve is a good sense element for the detection of a small magnetic particle that is attached to a DNA fragment as a label and immobilized onto the sensor surface. Since the particle is magnetic (under a DC bias field), it generates a magnetic field. The magnetic field may then affect the orientation of the free layer magnetization, causing a change in the electrical resistance of the spin valve.

[0052] The operation of a spin valve detector (**FIGS. 2A and 2B**) is described as follows:

[0053] 1) The magnetic nanoparticle under a DC bias field (H_b) generates a magnetic field around it. 2) The magnetic field will affect the resistance of a spin valve closely underneath it. 3) Application of an AC tickling field (H_t) will force the moment of particle to oscillate, resulting in an oscillating MR signal from spin valve. Note that in the in-plane mode the spin valve detector signal due to the magnetic nanoparticle has the same frequency f as the AC tickling field Ht, while in the vertical mode the signal has twice the frequency of H_t. 4) A lock-in amplifier is used to pick up such an oscillating signal with a high signal-to-noise ratio.

[0054] Spin valves have a magnetoresistive (MR) ratio of typically 5-12% and are used in hard disk drives to detect a magnetic bit made of only a few hundred closely packed Co alloy nanoparticles (size is about 10 nm) with a signal to noise ratio (SNR) of about 20 dB and a broad bandwidth of about 500 MHz. Therefore, it is theoretically feasible to detect a single Co nanoparticle of about 10 nm size in a narrower bandwidth or with lock-in detection. By narrowing the noise bandwidth, sufficient SNR is achieved even for single nanoparticle detection.

[0055] As a proof of concept, a prototype spin valve detector and detector arrays were prepared with a sensor width of about 1 μm or less (along the direction normal to the sense current through the spin valve and to spin valve thickness). It has been demonstrated that, after applying a diluted drop of 11-nm diameter Co nanoparticle dispersion on such detectors, we can obtain a signal amplitude of greater than 1 mV (peak-to-peak) from a 1 μm wide spin valve detector (Li, G., et al., *Journal of Applied Physics*, Vol. 93, no 10 (2003), p. 7557). The sensitivity of the spin valve detector depends not only on the magnetization and volume of magnetic tags and their distance from the free layer of the spin valve, but also on the geometry and bias field of the spin valve itself. We have found that narrower spin valves generally lead to a higher sensitivity. Consequently, spin valve detectors and detector arrays suitable for use with the present invention have sensor widths from about 0.01 μm to about 1 μm along the direction normal to the sense current and to spin valve thickness.

[0056] We have performed micromagnetic and analytical simulations of various spin valve designs extensively and summarize the signal (peak-to-peak amplitude prior to any preamplifier) due to a single Co nanoparticle versus spin valve free layer width in Table 2. Both the in-plane and vertical modes of operation (**FIG. 2B**) are listed. The distance from the particle edge to the midplane of the free layer is assumed to be 6 μm. The free layer strip is 2 nm thick and 3 μm long, but its active length (not covered by leads) is 1 μm. The sense current density is taken to be 10^8 A/cm^2, which is below the electromigration limit of the spin valve detector. The total detector thickness is about 34 nm. The magnetic moment of superparamagnetic Co nanoparticles have been calculated with the Langevin function.

[0057] We should have a sufficient signal level to detect a single 11-nm-diameter Co nanoparticle if the spin valve is made to be 0.2 μm wide and operated in the in-plane mode. Additionally, we can increase magnetic signal strength further by using FeCo-based magnetic nanotags, since the signal voltage is proportional to the magnetic moment in the tag.

TABLE 2

Spin valve signal voltage (peak-to-peak amplitude) versus free layer width. The voltage is due to a single Co nanoparticle with a diameter of 11 nm and its edge is 6 nm away from the midplane of the spin valve free layer. Both in-plane and vertical mode are listed, along with the relevant bias field and tickling field amplitudes.

		Free layer width		
		1 μm	0.2 μm	0.2 μm
		Sense current		
		10 mA	2 mA	2 mA
In-plane	(bias field, tickling field)	(100 Oe, 50 Oe)	(100 Oe, 50 Oe)	(100 Oe, 141 Oe)
mode	signal voltage	0.32 μV	2.1 μV	4.9 μV