Innovation in the Indian Semiconductor Industry: The Challenge of Sectoral Deepening

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Abstract

Seeking to build on related successes in other information technology sectors, the government of India has signaled its intent to transform the country’s performance in microelectronics. Facing a young and expanding population, India needs to create manufacturing jobs in promising industries, and it needs to build out from its limited high-technology base. Semiconductors are foundational in this regard. Today, there is much discussion within India about the link between semiconductors and innovation in bio-electronics, alternative energy production and storage, and various micro- and nano-devices. The government’s contemporary attempt to promote the building of infrastructure for manufacturing and applied research in semiconductors highlights reasons for hope. So too does the remarkable talent now available in the Indian diaspora. But significant impediments, especially in postsecondary and graduate-level education, must still be overcome if the necessary human capital is to be developed, equipped, and deployed effectively.

KEYWORDS: India, Indian industrial policy, high-technology innovation, semiconductor industry, microelectronics, nanoelectronics, education reform, electrical engineering, applied research

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India in Dynamic Global Markets

India is searching for its optimal place in the vital microelectronics industry, an important aspect of its emergence as a global economic power. It has achieved considerable capability in microchip design, but global industry leaders combine design with high-end manufacturing, applied research, and dynamic linkages with the broader sectors like information technology (IT) and biotechnology. With noteworthy success in software, business services, and pharmaceuticals already achieved, the government of India has signaled its intent to transform the country’s performance in microelectronics. Facing a young and expanding population, the country needs to create manufacturing jobs in promising industries, and it simultaneously needs to build out from its limited high-technology base. Semiconductors are foundational in this regard. Employment and industrial strategy are linked. Even if the industry itself will not employ great numbers of people, it supports productive processes in virtually all sectors that are well adapted to Indian advantages and requirements, and it links innovation in those sectors to important innovations abroad. Moving rapidly up the ladder of manufacturing, broadening the service sector, and harnessing a greater share of the gains from success in design—all indicate the desirability of India occupying a more significant place in global semiconductor production and innovation chains.

This brief case study, based on fieldwork undertaken in 2008, highlights the opportunities and the constraints facing India as it seeks to add value and exploit opportunities in the global digital economy. Today, there is much discussion within India about its role as a potential innovator in bio-electronics, alternative energy production and storage, and associated micro- and nano-devices. The government’s contemporary attempt to promote the building of infrastructure for manufacturing and applied research in semiconductors highlights reasons for hope. So too does the talent now available in the Indian diaspora. But many impediments remain—for example, in governing systems, national infrastructure, and human capital formation. Deficiencies in postsecondary and graduate-level education are emphasized in this study. Overcoming them is key if the necessary human capital for the industry is to be developed, equipped, and deployed effectively.

Semiconductors in India

In the decades following independence, India built an extensive scientific and engineering establishment. In certain sectors deemed critical to national welfare, it achieved notable successes. The leading facilities in this effort included the Indian Institute of Science in Bangalore, which dates from a Tata family initiative in
1909. The institute built up generally strong science and selectively capable engineering programs, and became central to the country’s post-1947 military establishment. A distinguished facility in Pilani, the Birla Institute of Technology and Science, traces its roots to 1929. After independence, it built a partnership with researchers at the Massachusetts Institute of Technology, made significant contributions in the computing, electrical engineering, and energy sectors, and in 1953 facilitated the creation of the government’s Central Electronics Engineering Research Institute (CEERI). The Tata Institute for Fundamental Research in Bombay (now Mumbai) began work in similar fields in 1945. After 1947, the government of India established seven Indian Institutes of Technology (IITs), mainly to train a skilled engineering workforce. (Today, some two hundred national laboratories and a similar number of autonomous but government-funded technical institutes exist. Two hundred and forty public universities and technology institutes, almost eighteen thousand public and rapidly expanding private colleges and institutes (including Indian Institutes of Information Technology [IIITs]), and nearly fifteen hundred private industrial labs round out the academic teaching and research infrastructure underpinning actual and potential innovation in semiconductor-related industries.

Indian scientists and engineers produced high-quality work in the early stages of semiconductor development during the 1960s, especially for military applications. Materials science was and remains a potentially strong area. Advanced electrical engineering on silicon is long established at IIT Bombay. The government’s Department of Electronics and Electronics Corporation of India—and eventually IIT Chennai, IIT Delhi, and IIT Kharagpur—built limited but respected capacity in certain microelectronic fields, like micro-electromechanical systems, and microwave device design. In the 1970s, however, a long competitive slide began (Vasi 2000; Sadagopan 2007). Companies in the United States, like Intel, IBM, Texas Instruments, and Motorola poured massive investments into early chip design and fabrication during the 1970s, and in the 1980s they were matched by national champions in Japan. Until a disastrous fire in 1985 destroyed its new fabrication facility near Chandigarh, India remained in the game to build faster and smaller silicon-based microchips, mainly through a governmental facility known as SCL (now the Semi-Conductor Laboratory in the Department of Space).

In the 1990s, SCL fell far behind new market entrants from East Asia. Simultaneously, however, the design and manufacturing functions in the globalizing semiconductor industry became separable. Designers could be located anywhere, as basic manufacturing processes in increasingly expensive fabrication facilities became standardized. “Fabless” design houses (firms that did not manufacture chips) began to proliferate wherever a critical mass of electrical engineering talent existed, and so-called foundries for mass production of
semiconductors came to be concentrated in Taiwan, South Korea, and Singapore (Ernst 2005a, 2005b, 2006; Herstatt et al. 2008; Keller and Pauly 2000; Tiwari, Buse, and Herstatt 2008). Not only did India enjoy a legacy in this regard but its potential pool of trainable and relatively inexpensive young talent was vast. In 1986, Texas Instruments was the first to recognize the opportunity after the government started moving away from the long-standing inward-focus of its industrial policies. Motorola, Philips, Intel, and other leading foreign firms soon followed.

In 1997, the government of India sought to build a high-end chip design industry by including it as a target sector in the ninth five-year plan. The stated goal was to increase total industry revenues in very large-scale integration (VLSI) to US$1 billion, or a 5 percent share of the global market. The policy instrument to accomplish this was a manpower training program at the undergraduate and graduate levels involving public expenditures of $3 million over five years. With an additional commitment of nearly $1 million, the program was eventually extended, first for one year and then until 2009. Lower-level training was provided by IITs in Allahabad, Hyderabad, Gwalior, and Pune, and graduate-training programs were developed at various IITs, especially IIT Madras (Dewey and LeBoeuf 2009: 54-56).

During the past decade, Indian software companies, like TCS and Wipro, have slowly begun to focus on the next wave of innovation sweeping the now-global industry. As silicon-based chip hardware innovation stabilized near its physical limits (i.e., at the end of Moore’s Law which holds that the number of transistors on a single chip doubles every two years), the leading edge focused on embedded software—increasingly complex, miniaturized, and multiple systems etched onto a single integrated circuit or chip. The main question was whether indigenous companies and Indian-based foreign multinationals could seize the day, at least in certain subsectors of the emerging systems-on-a-chip (SOC) technology. In this regard, some fabrication capability is essential, not only for prototyping, testing, and engaging in applied research, but for strategic purposes. Modularization and widely distributed production and supply chains provide powerful metaphors for the structure of high-tech industries in the twenty-first century. But at the leading edge of semiconductor industry, no great industrial power—from the United States to Germany to Japan to China—has let itself become entirely reliant on the foreign fabrication of microchips, especially those deemed critical to the most advanced applications.¹ For similar reasons, despite

¹ On 9 February 2009, for example, the CEO of Intel announced a $7 billion dollar investment in new chip-making capacity within the United States. At present, the global supply line widely perceived to be the most vulnerable because of concentrated production centers on standard memory chips (DRAMs).
accidents, infrastructural weaknesses, and mismanagement, India has thus far not reconciled itself to a niche strategy tied to software and design.

India’s Chip Manufacturing Challenge

In February 2007 the government of India announced a new national “Semiconductor Policy.” Its intent was to bolster India’s position in the dynamic global semiconductor industry, develop a capability to supply internal markets, and to meet the long-term challenge of fostering high-technology jobs for a growing educated population. The Department of Science and Technology (DST) was authorized to spend $2.5 billion to fund 25 percent of private-sector investments in semiconductor fabrication and manufacturing in related areas (GOI 2007a). The policy held the promise of financial incentives for de novo semiconductor fabrication, the production of liquid-crystal displays, organic light-emitting diodes, plasma display panels (PDPs), energy-storage devices, solar cells, and facilities for advanced assembly and testing. Fully aware of the modest size and lateness of the effort, officials claimed that the actual objective was not to create a globally competitive semiconductor manufacturing sector in the near term. Instead, the initiative was largely intended to stimulate some level of local chip production required to bring “spinoffs” indirectly to a range of related industries. It reflected a policy effort to create what officials in the Department of Science and Technology called a “handshake between software and hardware competencies” within India.2

Hands had in fact already started shaking a couple of years before the announcement of the Semiconductor Policy. By 2004, international chip companies had noticed that India’s domestic consumption of chips and related devices had already topped $10 billion per year. Widely quoted industry estimates extrapolated this market to $300 billion by 2016. In one widely noted move, Ajay Marathe, who in 2002 began building the Indian operations of US-based Advanced Micro Devices (AMD), left to help Vinod Agarwal, a prominent entrepreneur in the Indian diaspora, establish SemIndia. Working with both the government of India and the state government of Andhra Pradesh, SemIndia backstopped the new India Semiconductor Association—a trade group that now includes some seventy-five multinationals and local firms pushing the cause of manufacturing and marketing semiconductor chips and related products within India.

In 2006, SemIndia announced a $3 billion “Fab City” project, including a $100 million chip assembly and test facility. The project was initially based on a memorandum of understanding between SemIndia and AMD in December 2005

2 Interview with senior government official, New Delhi, 19 February 2008. Also see GOI 2006.
covering manufacturing, technology licensing and business development. In July 2008 the MOU with AMD expired in the midst of unfavorable economic conditions, and the prospects for SemIndia as a semiconductor manufacturing facility evaporated (Krishnadas 2008).

Soon after its inception, the focus at Fab City, located at Thukkuguda near Hyderabad, began to shift away from broad-scale semiconductor fabrication toward more specialized work. Because the cost of a state-of-the-art chip fabrication facility now exceeds $3 billion, it simply made economic sense for Indian chip designers to remain fabless, and to rely on prototyping, testing, and production abroad, especially in Taiwan. In the Indian design sector, many such collaborative partnerships already exist. In fact, under the terms of a September 2007 memorandum of understanding between the Indian Semiconductor Association (ISA) and the Taiwanese Semiconductor Industry Association (TSIA), production partnerships among member companies are actively encouraged.

In March 2007, Moser Baer Ltd. announced its intention to build a $250 million thin-film solar-panel-manufacturing facility, the world’s largest, whose modules were said to be cost-effective for rural applications.³ The National Semiconductor Policy and its incentives were expected to apply, and core technology was to be supplied by US-based Applied Materials. Signet Solar made a similar announcement a year later for a solar-cell facility in Chennai, also using technology from Applied Materials. Goldstone Infratech simultaneously decided to build a competing facility in Hyderabad using Korean technology supplied by Jusung Electronics.

On 18 February 2008, Minister of State for Commerce Jairam Ramesh addressed a conference of the Indian Semiconductor Association. He announced that five additional companies would take part in projects in Fab City. He also noted that this would bring the total investment there to $7 billion (Tippu 2008: 1). It was now obvious, however, that Fab City’s horizons had narrowed. In addition to some production of wireless components, computer equipment, and low-cost set-up boxes, the focus for the immediate future would be on alternative energy research, solar cell fabrication, and energy storage—but not on semiconductors.

In addition to SemIndia, sixteen companies were initially allocated land for manufacturing in Fab City. The leaders, in fact, targeted the manufacturing and marketing of thin-film solar cells. They included Moser Baer, Nano Tech Silicon, XL Telecom and Energy, KSK Surya Photovoltaic Ventures, Solar

³ Moser Baer Limited was established in 1983 as a unit in technical collaboration with Maruzen Corporation, Japan, and Moser Baer, Sumiswald, Switzerland. Later in the decade it moved into the data storage industry. The company, based in New Delhi, is today the only large Indian manufacturer of magnetic and optical media data storage products, like CDs and DVDs. According to information on the company’s website, it exports approximately 85 percent of its production.
Semiconductor, and Surana Ventures Ltd. Exploiting established technologies well adapted to the local environment, their growing operations proved that Indian firms could certainly master the manufacturing of high-technology devices using semiconductor materials. Beyond Fab City and similar centers in other states, however, national aspirations for the sector as a whole remained more ambitious.

The Indian Semiconductor Association (ISA) continued prominently and energetically to build support for expanded semiconductor design and indigenous manufacturing in India. Given the strength of India’s generic drug industry, the fruit of an earlier generation’s industrial policy, the biotech angle was also much discussed. To be sure, political interest was ignited, and many states began competing to provide land and other incentives to support their own new production zones. Devendra Verma, managing partner of the California-based investment company, Edgewood, for example, managed to attract some support for the idea of the Hindustan Semiconductor Manufacturing Company (HSMC). The company promised to produce chips for four applications: chipsets for mobile phones, direct-to-home-TV set-up boxes, automotive control, and smart cards. With Infineon Technologies as its key foreign partner, it promised to invest $1 billion to set up its first production line, using 90 nm and 130 nm processes and 200 nm wafers. Videocon, the consumer electronics manufacturer, also announced plans to spend $250 million to build a semiconductor facility; the company said it had found a technology partner and was scouting sites in West Bengal and Andhra Pradesh.

Close observers remained skeptical that a de novo Indian operation like HSMC could begin seriously to compete with foreign chip makers and that foreign firms themselves would contemplate production in India outside of niches like photovoltaics. At the same time, however, the conventional wisdom held that if any broad-scale Indian effort to catch up with global leaders were ever to succeed in this sector, the impetus had to come from within one of the country’s largest industrial conglomerates. Only they, it was commonly said, had the resources, foresight, and inside knowledge required to move governments beyond modest plans and build a solid local ecosystem capable of sustaining the move from advanced chip design to fabrication. In this context, much excitement followed the announcement in late May 2008 that The Reliance Group, headed by Mukesh Ambani, had lured Ajay Marathe from SemIndia to become chief executive officer for its future semiconductor operations. Significantly, however, Marathe began planning for those operations from his new base—in Silicon Valley.

Two years after the announcement of the National Semiconductor Policy, no company had yet actually invested in a broad-scale microchip fabrication facility in India (Rao 2008). Despite much talk about significant plans, skepticism regarding Reliance, SemIndia, HSMC, and other prospective manufacturers remained quite widespread. Not only had a severe downdraft hit the sector
worldwide, but the chips that Indian electronics-related firms actually needed at the moment could be sourced ever more inexpensively and efficiently from other places. Wipro, for example, maintained significant chip-design capabilities and a fabless division linked to the Taiwan Semiconductor Manufacturing Corporation (TSMC). Other firms, like Moser Baer, had no trouble working intimately with foreign-based semiconductor materials and tool suppliers.

Disquiet remained, however, in both government and corporate circles about whether it was wise to remain so dependent on external sources for the semiconductor-related technologies of the future. Speculation concerning a dawning new era of nano-technology spurred thinking about a fresh start. As the principal scientific adviser to the government of India, Dr. R. Chidambaram, noted, “We have missed the semiconductor revolution. But we cannot afford to miss the era of nano-engineering technology” (ISA Winwire, 13-20 July 2008). That sentiment remains widespread within India, especially at the intersection of advanced chip design and the biological and medical sciences. The key question remained whether it was wise from a national point of view to nurture high-end design capabilities at the micro and (soon) nano level, but then to let the serious returns from manufacturing innovative devices, applied research, and actual application in such fields as biotechnology accrue elsewhere. The stakes certainly became obvious in September 2008, when news came out about the design of a complete leading-edge microprocessor in India. An entirely Indian team of engineers at Intel’s Design Enterprise Group in Bangalore had designed from scratch the world’s first six-core x86 processor. All earlier versions had two or four cores, and all had reportedly taken much longer to design.4 (This signal achievement, of course, was based on a long line of Intel’s closely held proprietary technology.)

The success of Intel’s Indian engineering team drew attention to counterparts across the country’s information-technology sector (63% software and service exports, 17% software and services for domestic consumption, and 19% hardware, peripherals, and networking) (NASSCOM n.d.). Business services and software firms like Wipro, Tata Consulting Services, and Infosys, for example, have established a few “incubation centers,” with an estimated five to six thousand young people working on embedded systems—the linkage between semiconductors and software. Why should India not expect to earn a larger share of the net returns available in the global production and supply chains of which Indian firms are now a part?

Current annual turnover within India at the chip-software intersection is estimated at around US$ 4.6 billion, generated by an engineering workforce of just

over a hundred thousand, principally located in Bangalore, Noida, Hyderabad, Chennai, Pune, Ahmedabad, and Goa. A frequently cited study by ISA-Frost and Sullivan estimated total revenues in chip design in India of US$ 4.6 billion in 2006. The study projected the possibility that those revenues could expand to US$ 43 billion by 2015 (ISA-Frost and Sullivan 2007). At present, something like seven hundred new design houses start up in India every year, a number projected by the ISA to increase five-fold by 2015. In any case, of the established top fabless design houses in the world, ISA claims that nine are already operating in India, drawn by high-quality and relatively inexpensive indigenous talent. There remains a large gap, however, between the number of Indian engineers within the 100,000 currently capable of very-large-scale integration (VLSI) design work (600, according to one industry insider) and the 6,000 highly skilled engineers industry executives say that they currently need.

Despite this shortage at the top end, the fact that twenty-three of the top twenty-five global semiconductor companies now have operations in India is undoubtedly related to the competitive cost of technical talent—talent that could build significant export businesses. Those companies were also eager to stake out a position in India’s potentially gigantic internal market for semiconductors. Indeed, in certain applications, like cell phones, potential is already quickly maturing. Until the global downturn in 2008, overall semiconductor sales in India were growing at a rate of about 27 percent per annum (ISA-Frost and Sullivan 2007).

Against this background, foreign firms like TI, GE, Intel, Siemens, and Motorola energetically signaled their intent to help India build its ecosystem for innovation in this sector. They did so by expanding their own R&D operations and design centers, like the one that achieved the six-core microprocessor breakthrough for Intel, by supporting the creation of centers of excellence in selected IITs, and by providing fellowships and scholarships for promising students. Although national and state governments welcomed such support, ambivalence remained about what implications it held for India’s industrial future. Well-equipped foreign labs drained indigenous talent away from the universities, IITs, national labs, and domestic start-ups. Together with burgeoning research activities within the Indian business-services sector, lucrative opportunities aimed at near-term results discouraged talented Indian students from pursuing advanced scientific and engineering degrees. Without doubt, a vast pool of potential talent existed in the growing population. But filling and raising the quality of that pool remains a generational challenge. Ambitious immediate plans for the future within particular firms, however, had to confront the more critical challenge—quickly educating or attracting from abroad the scientists and engineers needed very soon to sustain appropriately targeted and constantly advancing innovation in semiconductor-related industries.
Again, as in other large countries, not least the United States, prominent voices inside and outside of government continue to question the wisdom of remaining dependent on innovation in such a key sector being orchestrated elsewhere. No doubt foreign chip makers are now engaged in more than “PR”&D inside India. But the difficulty of achieving a stable balance between market openness and deeper and broader national development in this sector is widely perceived within India. Only then, for example, would the country be able to leap ahead in more promising fields like bio-engineering, non-carbon energy generation and storage, drug discovery, and production of the kinds of micro- and nano-level medical devices likely to help meet the needs of a large and widely dispersed population.

The global economic crisis that began in the summer of 2007 reminded planners within India of the limits of export-led growth and the necessity of balancing external engagement with internal market deepening. Quite realistically, those charged with implementing the national Semiconductor Policy, as well as their counterparts in closely related sectors, refocused and redoubled their attention to India’s deficient postsecondary education system—a system that in 2007 produced only thirty-two PhDs in semiconductor-related disciplines and thirty-six in computer science.5

Building Scientific and Technical Infrastructure

Over the past five years, the Indian government increased annual funding for the IITs from $10-20 million to $40-60 million. It plans to more than double the number of IITs from seven to sixteen over the next five years. A major constraint, however, complicates the expansion plans described in India’s eleventh five-year plan. Even though they are among the elite technical institutions of higher education in India, the IITs are forced to rely on visiting and part-time faculty as a stopgap measure. Because they cannot attract enough highly qualified teachers, it is unlikely in the near to medium term that the IITs will be able to increase significantly the number and especially the quality of their graduates. The eleventh five-year plan is eloquent in its description of new institutions, but it is notably deficient in its strategy for filling them with qualified teachers and researchers.

Even if the government was seriously willing to ramp up the production of academic scientists and engineers, high demand for skilled labor mainly in the business services sector poses a significant impediment to their employment in advanced research in micro- and nano-electronics and in high-level engineering education. There are no reliable official statistics, but close industry observers

5 Estimate provided by Indian Semiconductor Association.
suggest that there are only about 450 PhD students now training in all engineering disciplines in India. The professoriate in both the IITs and the generally lower-ranked university system is aging rapidly, and even if they all stayed in the academy, that cohort is too small. And of course, no one expects most of them to do so. One of the ironic consequences of a fast-growing and more open economy is an environment where promising teaching and research talent is taken too soon directly into industry, especially business-process outsourcing, where salaries, benefits, and amenities are much more attractive than they once were and certainly much more attractive than the academy can offer. In fact, many young Indians who might have pursued MTech, MS, or PhD degrees just a few years ago are not doing so today. Most significantly, even when students do complete advanced degrees in engineering or science, business process outsourcing (BPO) firms offer them starting salaries of up to seven times the wages of their professors.

In this respect, the business-services boom was a mixed blessing. Whether it remains even that is a pressing question during a spreading recession but, in a rapidly changing global context, it continues to shape perceptions of realistic opportunities for young Indians in the near term. Although the boom provided good jobs to lower-skilled engineers and technicians, it also skewed the Indian economy and undercut long-term educational values and priorities. Official data provided to the US National Science Foundation by various Indian sources gives a somewhat brighter picture for recent years. The trend, nevertheless, is unmistakable, particularly when compared to other Asian countries.

Over the past twenty-five years, India has made very little progress in raising the number of engineers it educates to the doctoral level (Agarwal 2006: 61). The most direct comparison is China because its billion-plus population is similar to India’s. In the years 1985 to 2003 the number of engineering PhDs conferred by Indian universities fluctuated between 298 and 779. By contrast, that number in China rose steadily each year from 68 in 1985 to 8,054 in 2004. When compared to countries with only a small fraction of its population, India looks decidedly anemic. In recent years, for example, Taiwan (pop. 22.9 million) has trained about the same number of PhD engineers as India at the high end, but South Korea (pop. 48.9 million) has exceeded India by nearly a factor of three.  

Moreover, the quality of Indian PhD-granting institutions varies greatly. Some PhDs can be obtained in as little as eighteen months, whereas others take an average of three to four years. The standard of graduate evaluation seems also to be low and variable. “While inquiring about the status of higher education in Bihar, [an investigating committee set up by the government] found out that a

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6 NSF 2008, Appendix Table 2-43. An Indian source, the University Grants Commission, gives roughly the same numbers for engineering doctorates granted by Indian universities and institutes, averaging only about 700 per year.
single thesis was used by as many as eight students for award of PhD in Bihar universities” (Agarwal 2006: 65). According to a much-cited Chinese-based academic-ranking exercise, no Indian university was ranked among the top three hundred universities globally in 2008, and only two made the top four hundred: IISc Bangalore and IIT Kharagpur (Institute of Higher Education, 2008). Times Higher Education also publishes world university rankings. In 2008 no Indian university appeared in its list of the top two hundred universities in the world.  

India graduates far fewer engineers than scientists; in fact engineers make up only 12 percent of the science and engineering (S&E) doctorates awarded by Indian universities. This contrasts sharply with China, Taiwan, South Korea, and Japan, where engineers make up between 51 and 58 percent of all S&E degrees awarded. These data clearly point to one attribute of India’s manufacturing deficit: the country has not created a large enough pool of top-level engineers who would be motivated to teach younger people and lead the way to the establishment of a robust manufacturing economy. The other countries in this sample—China, Taiwan, and South Korea—all excel in manufacturing, a reflection of the engineering acumen they have developed.  

Related to the question of training scientists and high-level engineers for the future, there is a clearly defined hierarchy and division of labor in R&D in India. The Indian national labs today conduct good theoretical and basic experimental research, but the infrastructure supporting this work has suffered from underinvestment for many decades. Taken together, the national labs now host about four hundred PhD candidates in the Science and Engineering disciplines at any given time. (Actual degrees are still awarded by particular universities.) At the next level, the IITs conduct a small amount of applied research, but much of their work is contracted for immediate commercial use by business firms. On their own, the top twelve central universities remain focused on theoretical work and teaching. Many do not have up-to-date textbooks and, again, they cannot fill all vacant faculty positions. The distant third-tier, the IIITs (so-called triple IIts, Indian Institutes of Informational Technology) and thousands of similar private colleges, in some cases now affiliated with foreign universities, provide basic technical/engineering training, typically for only two or three years. Many are “job shops” that conduct product modification for local firms.  

By the numbers, India has what appears to be a wealth of educational institutions, even before the expansion envisaged in the eleventh five-year plan. According to one source, the number of institutions of higher learning in India rose from approximately 13,000 in 2000-01 to about 18,000 in 2005-06. Nearly

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8 Calculated from NSF 2008, Appendix Table 2-43.  
9 A more detailed view of growth trends in the Indian system of higher education must include “deemed universities,” like the Tata Institute for Fundamental Research in Mumbai, which was
all of the growth, however, has occurred in private institutions of suspect quality that do not receive funds from India’s central or state governments (Agarwal 2006: 13-14). Of these institutions, about one thousand claim to provide engineering background of various kinds, mainly catering to the immediate personnel needs of India’s business services industries. Some combine college-level instruction with product engineering. Only about 10 to 15 percent of their students, however, are trained sufficiently to be attractive to companies like Wipro and Infosys or the Indian affiliates of foreign-based multinationals. Infosys, for example, recruits from some 200 to 300 private institutions. In the best firms, the training of recruits from such institutions is augmented internally by company “universities.”

Including IITs and technical colleges, India today provides very basic engineering training for approximately 222,000 students each year. This compares roughly with 498,000 per year in China. In the United States, 100,000 engineering degrees are granted annually.10 (Industry insiders widely note a very significant quality gap that continues to favor the United States.) According to ISA-Ernst and Young estimates, which are on the optimistic side, India now possesses a vast pool of some 1.75 million people with at least basic technical engineering skills, exceeded only by the United States and China, each with just over two million. At the same time, the pool of talent from which future workers in the Indian semiconductor industry can be drawn stands at around 75,000, more than any other country except the US, which still exceeds India by a factor of four. The comparable figure for China is 10,000 and for Taiwan 20,000 (ISA-Ernst and Young 2006: 22).

However, as we noted earlier, at present only about six hundred individuals from that vast Indian pool are actually now engaged in designing microchips at the most globally competitive level. Of course many others are capable of working at a lower level, for example, adapting designs for local applications. At that level, best estimates put the number of designers at work in both India and China at around five thousand each. Those same estimates show that despite the lack of fabrication facilities in the country, Indian salaries overall are 25 percent higher than the salaries in China, at $15,000 and $12,000 per year respectively.11 Aware that much manufacturing process innovation in the industry

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10 In 2005, US institutions of higher education graduated 66,133 degrees at the BSE level, 34,099 at the MSE level, and 6,551 at the PhD level—a total of 106,883 (NSF 2008, Appendix Table 2-1).

11 Brown and Linden 2006.
occurs on or near the shop floor, and that perceptions of India’s somewhat better protection of intellectual property rights may be changing, Indian industrial planners are not sanguine about this gap.

Unlike the situation forty years ago, government labs have done little to build the new cohort of competitive talent in this sector. Inadequate facilities and the inability to buy state-of-the-art equipment effectively remove government labs from semiconductor work of anything other than a highly theoretical nature. As the director of one of the premier government labs bluntly put it:

My personal vision is that in ten years all the government labs overall will disappear because we will not be able to compete for talented people. The best-equipped labs in the country will soon bear the names GE or TI, and our very best people will be attracted to them. While there are a few pockets of high-quality research in the country, the sad truth is that university research in almost all fields is inadequate. In semiconductors, the problem has been compounded by the fact that serious research is very capital intensive, and we have had no industrial base to support and nurture it. In the 1960s, government researchers had some pretty good work going on in the semiconductor field, but then we could not afford the clean rooms. About all we now have is at the Central Electronics Engineering Research Institute (CEERI) in Pilani, which recently acquired a small fab able to work efficiently on six-inch wafers at a 1 micron design rule. This is okay only for some limited purposes.12

Company labs within India already try to fill some of the gap between the high-end talent needed and that which is actually available. Labs operated by subsidiaries of foreign-based electronics companies are widely deemed to be the best equipped in the country. In the chip-design field, they far exceed anything comparable in the government’s national labs, the IITs, and university labs. They provide a serious training ground for local talent, and they try to retain the best engineers they are able to attract. The focus of work in the labs remains almost entirely external. They create and adapt products and solve problems under strategic directions provided from abroad. There are limited exceptions, where Indian employees now collaborate on a more or less even footing with their counterparts in advanced industrial countries. In some cases, Indian teams compete for world product mandates. Unlike in the early days of independence, when prominent multinationals were forced to leave India, those corporate labs

12 Interview, New Delhi, 20 February 2008. Industrial work globally below .4 micron is now common, and advanced lab work is now advancing quickly at far smaller levels.
are now widely acknowledged to be positive contributors. They can claim a large share of the credit, for example, for training many of the country’s high-end VLSI designers. Still, dark fears exist among Indian academics and industrial planners that the successful efforts of multinationals are locking India into a secondary position in the emerging global division of high-tech labor.

Despite such fears, university labs remain in a far worse condition than government labs. No serious policy responses are yet in sight. Almost all equipment must be imported because India’s manufacturing base remains so limited. Aside from antiquated tools, deficiencies in the most basic electrical, water, waste, and communications systems are especially problematic across the board. Only rarely, however, does semiconductor-related work at a select few universities and IITs come even close to applied innovation. Faculty members are quite literally overwhelmed by teaching obligations and short-term consulting work. Carving out time for serious research is difficult. The best scholars are also significantly underpaid. Universities are governed by strict and outmoded regulations, and salaries are rigidly tied to civil-service pay scales. In a big change from the post-1947 period, young people no longer see a university-based research career as prestigious or particularly attractive. There are limited opportunities for providing special incentives to promising talent. As one senior government minister put it, “Indian institutions of higher education are generations behind the US. By comparison, even the elite IITs are groping in the dark” (Interview, New Delhi, 21 February 2008).

The faculty supply and compensation dilemmas pose formidable obstacles. Some universities are experimenting with fellowship schemes, and many institutions permit outside contracting and also now have royalty-sharing arrangements in place. But big bottlenecks remain. It is common to hear of the civil service, itself shaped by both a strict regulatory mentality but also by widely reported ethical lapses, as a giant yoke holding back innovation in India. While wise and good officials do exist and can credibly claim some responsibility for India’s progress in recent decades, it remains common for entrepreneurial business people to highlight caste, bureaucratic, and other restraints that have impeded development and social mobility. In high-tech sectors, like the semiconductor industry, there is also a residue of concern about less-than-adequate official enforcement of intellectual property rights.

Establishing a solid regime for protecting intellectual property is certainly important if indigenous innovation is to flourish. But the more fundamental reform lies in educational and training systems, which only government can undertake. With this in mind, the prime minister convened a “National Knowledge Commission,” under the chairmanship of Sam Pitroda, who played a prominent role in opening up India’s telecommunications industry. Its report, released with much fanfare in 2007, noted: “There is still resistance at various
levels in the government to new ideas, experimentation, process re-engineering, external interventions, transparency and accountability, due to rigid organizational structures with territorial mind sets” (National Knowledge Commission 2007: 3). In that context, the commission recommended sweeping reforms in regulatory regimes governing education, openness to diversity, decentralization, and experimentation across the system, as well as the acceptance of potentially significant differentials in salaries and research opportunities at higher levels. Only bold new thinking could promise the kind of reforms necessary to meet rapidly rising demand for education at all levels and to stay competitive with other emerging-market countries, like China.

Beyond education and training gaps, the challenge for high-tech industries within India is indicated by governmental and private-sector R&D expenditures. Private-sector funding is rising in this area, but it still lags government funding significantly. As the World Bank reported in 2008, “most indigenous spending on R&D in India is still by the public sector, where India has a strong record in the production of basic knowledge. However, very few patents from publicly funded R&D are commercialized, and the Indian private sector has very little interaction with public R&D institutes and universities” (World Bank 2008: 1-2). In fact, the public sector accounts for nearly 80 percent of R&D spending, of which only 4 percent flows through institutions of higher learning. Electronics, chemical, and defense-related industries each account for about 10 percent of annual R&D expenditures. There are small outlays in telecommunications (4%), engineering (2%), and information technology (2%). In contrast, combined R&D spending in biotechnology and pharmaceuticals amounted to about 45 percent of the annual total. 13

The Indian Diaspora

India clearly requires many more highly qualified and much-better-equipped scientists and (especially) engineers if it is to build an innovation ecosystem adequate to the size and potential global influence of its internal market. The estimates for technical workforce requirements in the following table give a survey-based sense of the scale of the challenge for electronics and all other R&D-intensive sectors.

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13 Sixty-two percent comes from the central government and nearly 9 percent from state governments (GOI, 2007b: 3).
Estimated Demand for Qualified R&D Professionals in India, 2005-2020

<table>
<thead>
<tr>
<th>Professional Type</th>
<th>2005</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>PhDs required</td>
<td>27,000</td>
<td>56,000</td>
<td>87,000</td>
<td>110,000</td>
</tr>
<tr>
<td>Postgraduates</td>
<td>80,000</td>
<td>168,000</td>
<td>261,000</td>
<td>329,000</td>
</tr>
<tr>
<td>(MTech, MS, ME)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graduates</td>
<td>159,000</td>
<td>336,000</td>
<td>524,000</td>
<td>659,000</td>
</tr>
<tr>
<td>(BTech, BS, BE)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>266,000</td>
<td>560,000</td>
<td>872,000</td>
<td>1,098,000</td>
</tr>
</tbody>
</table>

Source: Alok Aggarwal et al., 2006.

Although India’s educational system is unlikely to meet the need for highly educated scientists and engineers in the near term, the Indian diaspora provides semiconductor and other high-tech firms in India with a potentially key advantage as they seek to move up the global value chain. Despite mixed feelings about the diaspora within India, feelings shaped by the country’s early post-independence history, that advantage today is becoming widely recognized (Kapur 2002). Since 2000, foreign-trained (mainly US) students with science and engineering Master’s and PhD degrees have been critical to building successful business services and software operations within India. When Indians go abroad to earn degrees in science and engineering, they have tended not to return. Many, however, have remained engaged in networks of science and engineering that span the globe and prominently interact with researchers and institutions in India. The most obviously successful Indian enterprises since the policy turn toward economic liberalization in the late 1980s exploited such networks.

During the two decades following 1985, some eight thousand Indian citizens earned doctorates in engineering in the United States, compared to thirteen thousand from China and nine thousand from Taiwan. Most Indians stayed for at least five years after the award of their doctorates, a number that has remained fairly constant near 90 percent per annum since the early 1990s. This is similar to the Chinese experience but contrasts sharply with that of Taiwan and South Korea, well over half of whom soon returned to their countries of origin.

A different picture emerges with regard to the education abroad of Indian undergraduates. In the two-year period between 2006 and 2007, about 14,800 Indian students enrolled in undergraduate science and engineering programs at US universities compared to 779 for Indian universities (NSF 2008, Appendix Table 2-33).

14 “Survey of Earned Doctorates,” special tabulations, NSF, 2008, Table 2-9. It is also interesting to note that in 2005, the latest year for which data are available, Chinese universities produced 8,054 engineering doctorates compared to 779 for Indian universities (NSF 2008, Appendix Table 2-33).
15 NSF, 2008, Appendix Table 2-33. Also see Finn 2003.
universities, of which about 5,100 or 53 percent studied engineering (NSF 2008: Appendix Table 2-17). Lately, those students appear to be going home again in increasing numbers. According to one report, “What began as a trickle in the late 1990s is now substantial enough to be talked about as a ‘reverse brain drain.’ By one estimate, there are 35,000 ‘returned nonresident Indians’ in Bangalore, with many more scattered across India” (Waldman 2004). The business process outsourcing (BPO) boom was clearly in the background. NASSCOM, the trade group that represents Indian IT and BPO companies, “estimated that 30,000 technology professionals have moved back [in 2004 and 2005]. Bangalore, Hyderabad and the suburbs of Delhi … with their Western-style work environment, generous paychecks and quick career jumps, offer the returnees what they could only get in Palo Alto or Boston until now” (Rai 2005). During the recession that began in the United States in 2008, a serious push factor has matched this pull factor, as H1-B visas for postgraduate employment have become more difficult to obtain.

All things considered, the following picture emerges: the seven elite IITs choose their annual entry classes from a pool of applicants that now exceeds three hundred thousand and they each graduate from 1750 to 2100 students per year. Over the past couple of decades, the biggest change is in what those graduates do afterwards. Where the vast majority used to go abroad for further scientific and engineering education, usually to the United Kingdom and the United States, now only a small minority do so, mainly because of opportunities for immediate employment within India’s high-end business services and software companies (Interview, senior academic administrator, Bangalore, 11 February 2008). Undergraduate as well as graduate degrees earned abroad nevertheless retain a high prestige value back in India. Attracting human capital from the diaspora is an obvious source of future competitiveness in all high-tech sectors, not least in the semiconductor industry. Whether skilled individuals return home or not, Indian high-tech networks are ever more significant. When top talent does return home, leading multinationals remain committed to following them. The Intel case recounted above is highly suggestive in this regard.

Conclusion

India’s recent success in chip design, software development, and business services is remarkable. Because widely shared aspirations to build upon these foundations are not unrealistic, government has committed to key industries on the hardware side of information technology. The national Semiconductor Policy initially met with enthusiasm in business circles linked to the Indian diaspora but then encountered skepticism reinforced by a global downturn in the semiconductor industry. Anyone examining present and possible future sites of related manufacturing activity in this sector will notice staggering impediments to putting
appropriate and competitive infrastructure in place—from funding deficits to insufficient water, electrical, transportation, and communication systems. However, India needs manufacturing jobs in promising sectors and it has already proven that it can create them in niches like solar cells. Rapid growth in wireless telephony and in pharmaceuticals, moreover, suggests new possibilities for connections between chip design, new generations of wireless micro- and nano-devices, and bio-engineering. In this regard, Juzer Vasi, pioneering professor of electrical engineering at IIT Mumbai, was prescient in 2000 when he wrote, “Perhaps India does not need a state-of-the-art multi-billion dollar fab. But it must always have two or three reasonable-size foundries, which can provide backups to international foundries, and be used for strategic and special purpose designs, for which international foundries may not be appropriate” (Vasi 2000).

India is trying to move ahead in semiconductor-related industries, struggling to build on and not be trapped by a narrow business-services-consulting model of development, one that promises neither enough employment nor an expansive platform for future value-added innovation. Chip design at the high-end represents a first significant step. It is based in part on the legacy of government programs in the post-1947 period, but now mainly on labs built by foreign semiconductor companies or on partnerships between fabless design houses and foreign foundries. Both domestic and foreign industrialists, deeply networked in the diaspora, are beginning to take the next steps. When markets turn up again, they will try not only to build platforms for exports but production systems to help realize the vast potential of the Indian market.

Daunting obstacles face the next generation of industrial planners in this and related sectors. Most prominently these include a deficient system for educating the requisite numbers of high-quality engineers and scientists as well as a dilapidated infrastructure of facilities capable of sustaining advanced education, applied research, innovation, prototyping, testing, and (eventually) device fabrication. The government of India has targeted these problems, but the dilemmas it confronts are deep and difficult. Diagnosis and the announcement of new institutions are clearly insufficient.

For an array of reasons that we’ve suggested, there is a yawning gap between the number of qualified teachers and researchers likely to be available and the number actually required. India also remains far behind other large countries in its public and especially private-sector investments in R&D. This is a massive generational challenge, the urgency of which may be measured against the backdrop of internal demographic pressures and external competition from China and other quickly developing countries. In semiconductor and semiconductor-related industries, Indian democracy faces the immediate task of tangibly proving its worth. The deepest challenges are internal, but an important source of support and advantage lies in the Indian diaspora. Future policies might
wisely continue to target the ideas, energy, and investments embedded in now-
dense global networks.

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